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Electromagnetics Engineering Office
Propagation Engineering Division
Technical Report EMEO-PED-81-4

MUTUAL COUPLING IMPEDANCE BETWEEN THE HF CENTER-FED FIRST-RESONANT DIPOLE ANTENNA AND EARTH - NEC SOLUTIONS

By
Harold F. Tolles

April 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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I. INTRODUCTION.

The purpose of this report is to validate the Sommerfeld subroutine in our CDC-6500/6600 NEC program, and to present the results for the standard HF first-resonant dipole antenna in graphic form for analysis, reference, and subsequent comparisons.

Our original AMP (Antenna Modeling Program) used the Fresnel RCM (Reflection Coefficient Method) to obtain antenna-to-ground mutual coupling impedance, and it has been pointed out that a Sommerfeld method must be used when the height, H_λ, of any part of the dipole over earth is less than[1,2]

$$H_\lambda < \frac{0.70}{\sqrt{|\varepsilon|}} \quad \text{wavelength} \qquad (1)$$

where,

$$\varepsilon \doteq \varepsilon_r - j\,\frac{1.79751 \times 10^4\ \tau}{f_{MHz}} \quad \text{numeric}$$

ε_r = earth's relative dielectric permittivity; numeric

τ = earth's conductivity; mhos/meter

Using the HF frequency range together with earth's electrical properties listed in Table I, equation 1 is plotted on Figure 1.

The results plotted on the next 50 graphs are mutual impedance, R_{21} and X_{21}, solutions. These solutions were obtained by using NEC to compare the antenna's self (free-space) impedance, Z_{11}, with the antenna's input impedance, Z_{in}, when near the earth as follows.[3]

when the antenna is horizontal:

$$Z_{in} = Z_{11} + (-Z_{21})$$

$$Z_{21} = Z_{11} - Z_{in} \quad \text{ohms}_{11} \qquad (2)$$

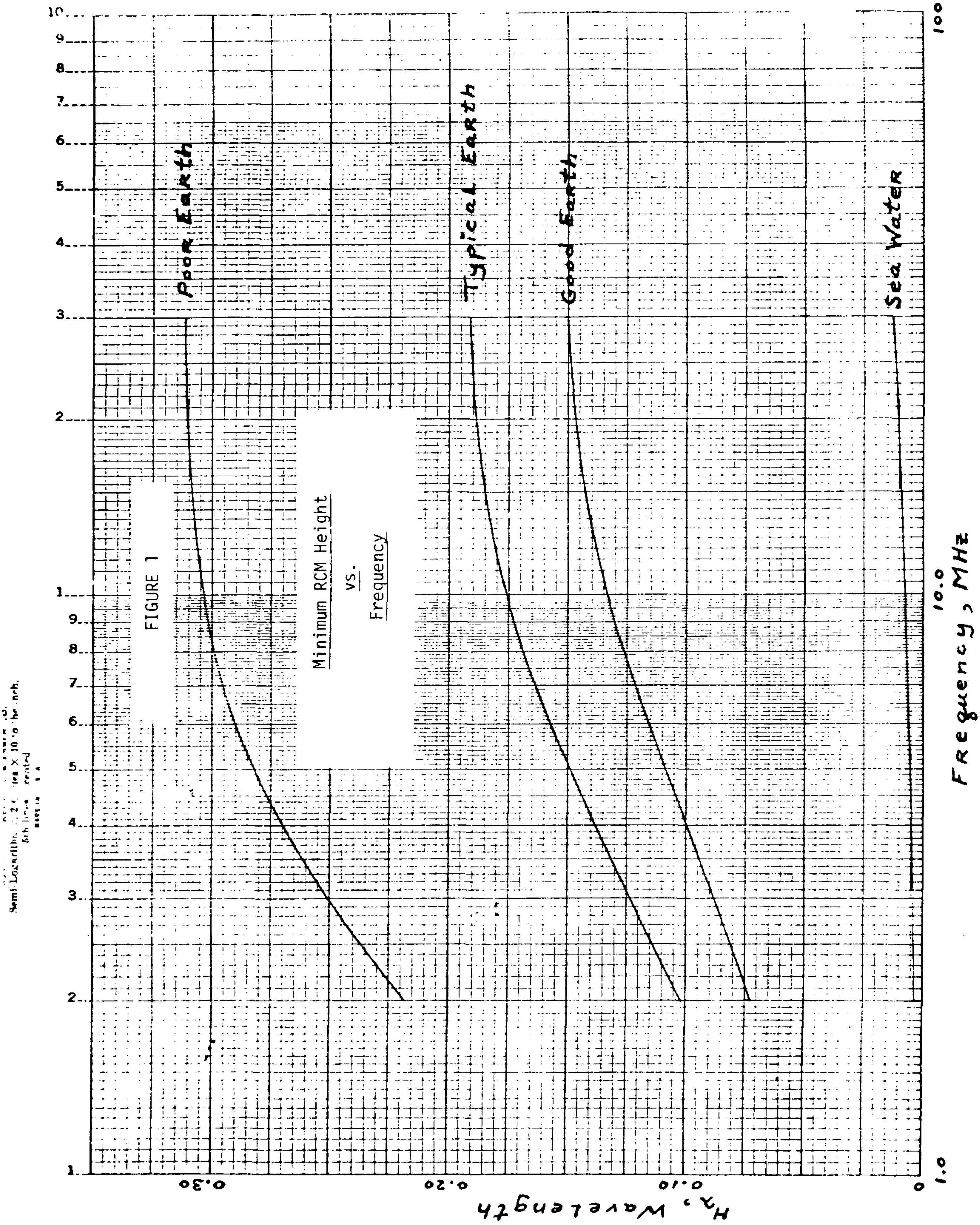


FIGURE 1

Minimum RCM Height vs. Frequency

when the antenna is vertical:

$$Z_{in} = Z_{11} + (+ Z_{21})$$

$$Z_{21} = Z_{in} - Z_{11} \qquad \text{ohms}_{\perp} \qquad 3$$

Since the antenna was pruned to first-resonance, $Z_{11} = R_{11}$, and equations 2-3 reduce, respectively, to:

$$Z_{21} = R_{11} - Z_{in} \qquad \text{ohms}_{11} \qquad 4$$

$$Z_{21} = Z_{in} - R_{11} \qquad \text{ohms}_{\perp} \qquad 5$$

The first-resonant dipole self resistance, R_{11}, used in equations 4 and 5 can be approximated without having to resort to the computer NEC program. The procedure is to use an estimated relative velocity, $V_r(e)$, multiply $0.5\lambda_o$ by this $V_r(e)$ to get an actual length, L, divide L by the wire diameter, D, and solve equation 4 of reference 4 for an actual relative velocity, $V_r(a)$. The process is repeated (iterated) until $V_r(a) = V_r(e)$.

When each $V_r(a)$ thus obtained is used as the next $V_r(e)$, the solution $V_r(a) = V_r(e)$ is obtained via a relatively few iterations because of rapid convergence. Then, note L/D when $V_r(a) = V_r(e)$, and use this L/D in equation 9 of reference 4 to obtain R_{11}. The following is an example solution:

$$V_r(e) = 0.976772 \qquad \text{numeric}$$

$$0.5\lambda_o \doteq 2950.718504 \quad \text{inches at 2.0 MHz}$$

$$L \div (0.976772)\ (2950.718504) \doteq 2882.179215 \text{ inches}$$

$$D = 0.08081 \qquad \text{inches (\#12 wire)}$$

$$V_r(a) \doteq 1 - [10.541 \log_{10}(\tfrac{L}{D}) - 4.933]^{-1}$$

$$\doteq 0.976772 = V_r(e) \qquad \text{numeric}$$

$$\therefore Z_{11} = R_{11} \doteq 73.0 - \left[0.252 \log_{10}\left(\frac{2882.179215}{0.08081}\right) + 0.232\right]^{-1}$$

$$\doteq 72.275 + j\ 0.0 \qquad \text{ohms}$$

when these L and D values are used in the computer NEC program, the free-space solution at 2 MHz is

$$Z_{11} \doteq 72.330 - j\ 0.340 \qquad \text{ohms}$$

Thus, when L/D $\doteq$ 35666, the above procedure gives a solution that is within 0.06 ohms and 0.27 degrees of that obtained via NEC at 2.0 MHz!

To obtain the effect of frequency upon the results, the 2-30 MHz band was divided into 4 MHz increments. Then, with the exception of solutions over a perfect earth, 8 frequencies are used in this analysis. Where less than 8 curves appear on the imperfect earth graphs, curves are combined when the error is less than plus-minus 1.5 ohms.

To obtain the effect of earth's electrical properties upon the results, 5 defined earths are used. The arbitrary properties are listed in Table I.

TABLE I

Earth	ε_r (numeric)	τ (mhos/meter)
Poor	5.0	0.001
Typical	13.0	0.005
Good	21.0	0.010
Sea Water	80.0	5.000
Perfect	1.0	∞

The normalized height arguments, H_λ, shown on the graphs are feed heights over the earth. Thus, the remote end of one arm of a vertical center-fed first-resonant dipole antenna is very close to the earth when H_λ = 0.25.

The curves on the enclosed 54 figures were generated from 9942 calculated data points. Thus, the enormous amount of required computer plus reduction time precludes the inclusion of other antenna types in this report.

II. HORIZONTALLY-POLARIZED MUTUAL RESISTANCE.

The mutual resistance, R_{21}, results are plotted on Figures 2-6, 7-11, 12-16, and 17-21 for height, H_λ, intervals of 0.001-0.015, 0.015-0.155, 0.15-0.85, and 0.85-1.55 wavelengths, respectively. Thus, at each height interval, there are 5 graphs, one for each defined earth, and the frequency or frequency range is plotted on each graph.

With the graphs so arranged, some degree of earth interpolation is enhanced. As an example, let the earth's electrical properties be $\varepsilon_r = 10$ and $\tau = 0.002$ mhos/meter (between poor and typical earth). Using Figures 2 and 3 with $H = 0.01\lambda_o$ and $f = 2.0$ MHz, the solution is $-35.3 < R_{21} < +3.0$ ohms. The NEC solution is -18.8 ohms.

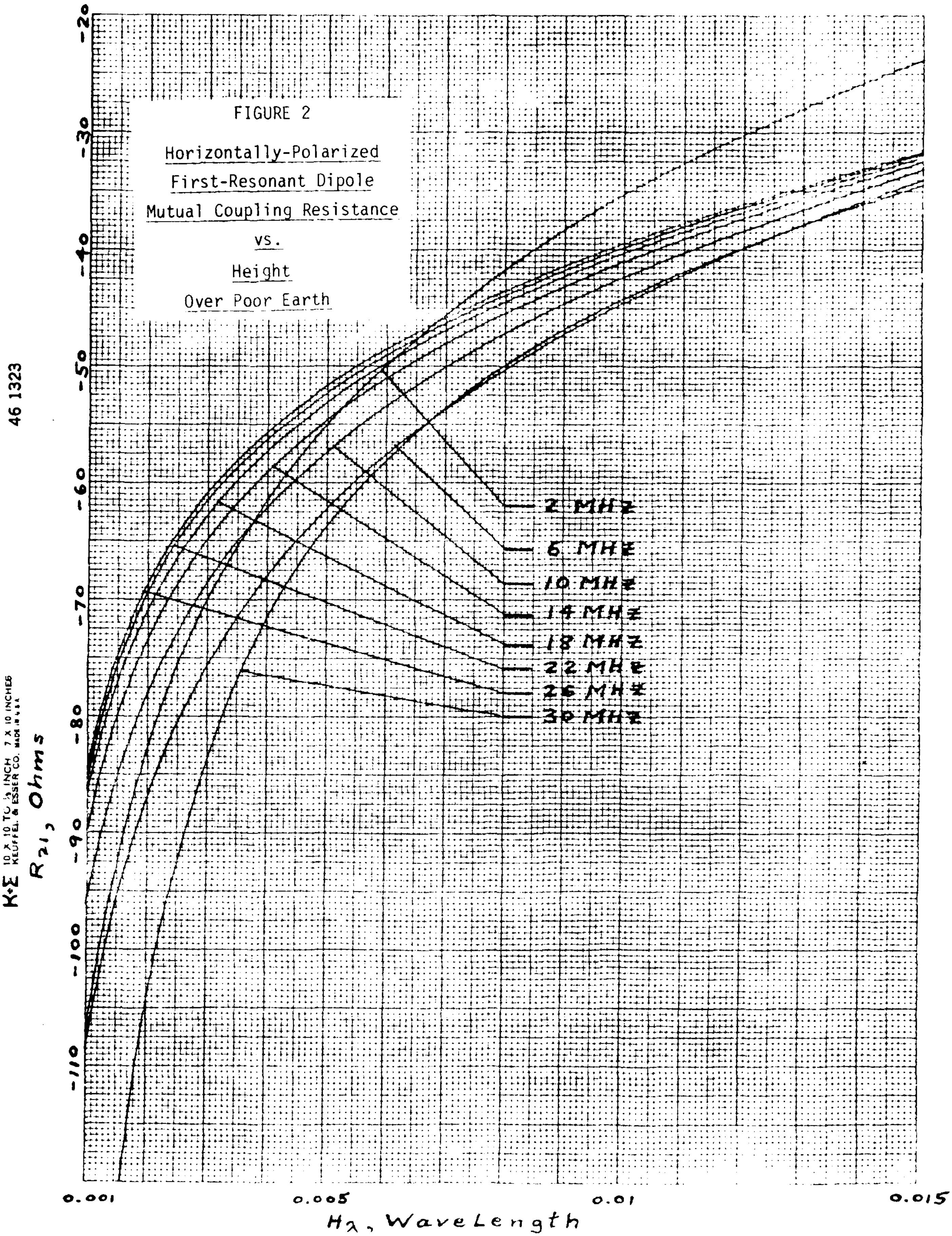
These figures show that ground (<u>not</u> sea water or perfect earth) mutual resistance is <u>highly</u> negative when this antenna is <u>near</u> an inperfect ground which, from equation 4, <u>increases</u> the antenna resistance drastically. This conclusion is supported by field measurements.[5,6,7,8]

The results shown on Figure 5 appear to be highly frequency sensitive when this antenna is <u>near</u> sea water. The loss tangent of sea water does not exhibit a relatively strong displacement current until the frequency is above 1.0 MHz. The <u>great</u> difference in R_{21} solutions between 26 and 30 MHz was not expected, and the reason for this is given in the Summary.

The results shown on Figure 6 are what one would expect. The mutual resistance, R_{21}, approaches the dipole self resistance, R_{11}, when the height, H_λ, approaches the dipole radius, and the dipole self resistance, R_{11}, is a function of L/D. For practical reasons, number 12 wire (diameter = 0.08081 inches) was used at all frequencies except 30 MHz

FIGURE 2

Horizontally-Polarized First-Resonant Dipole Mutual Coupling Resistance vs. Height Over Poor Earth



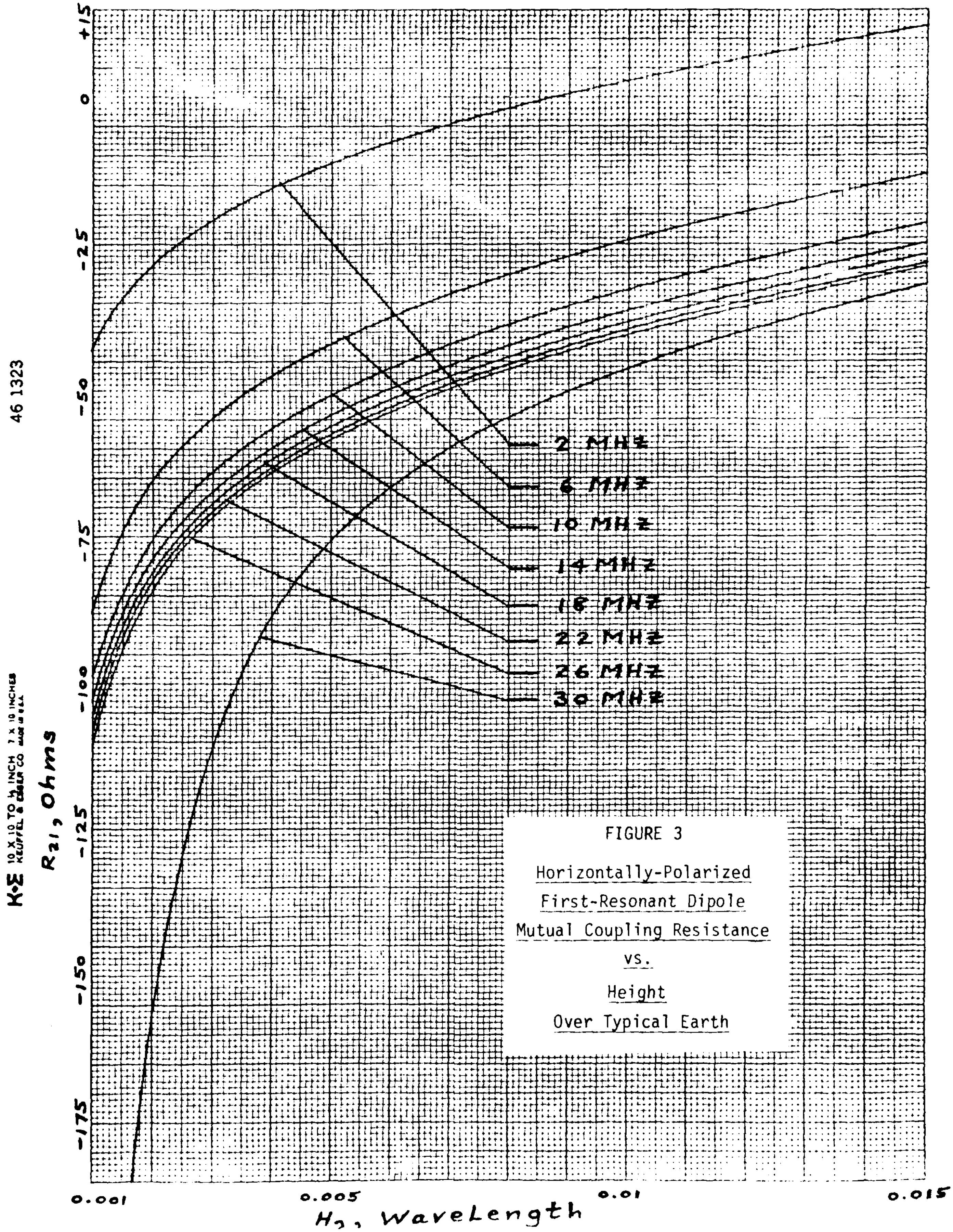


FIGURE 3

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Typical Earth

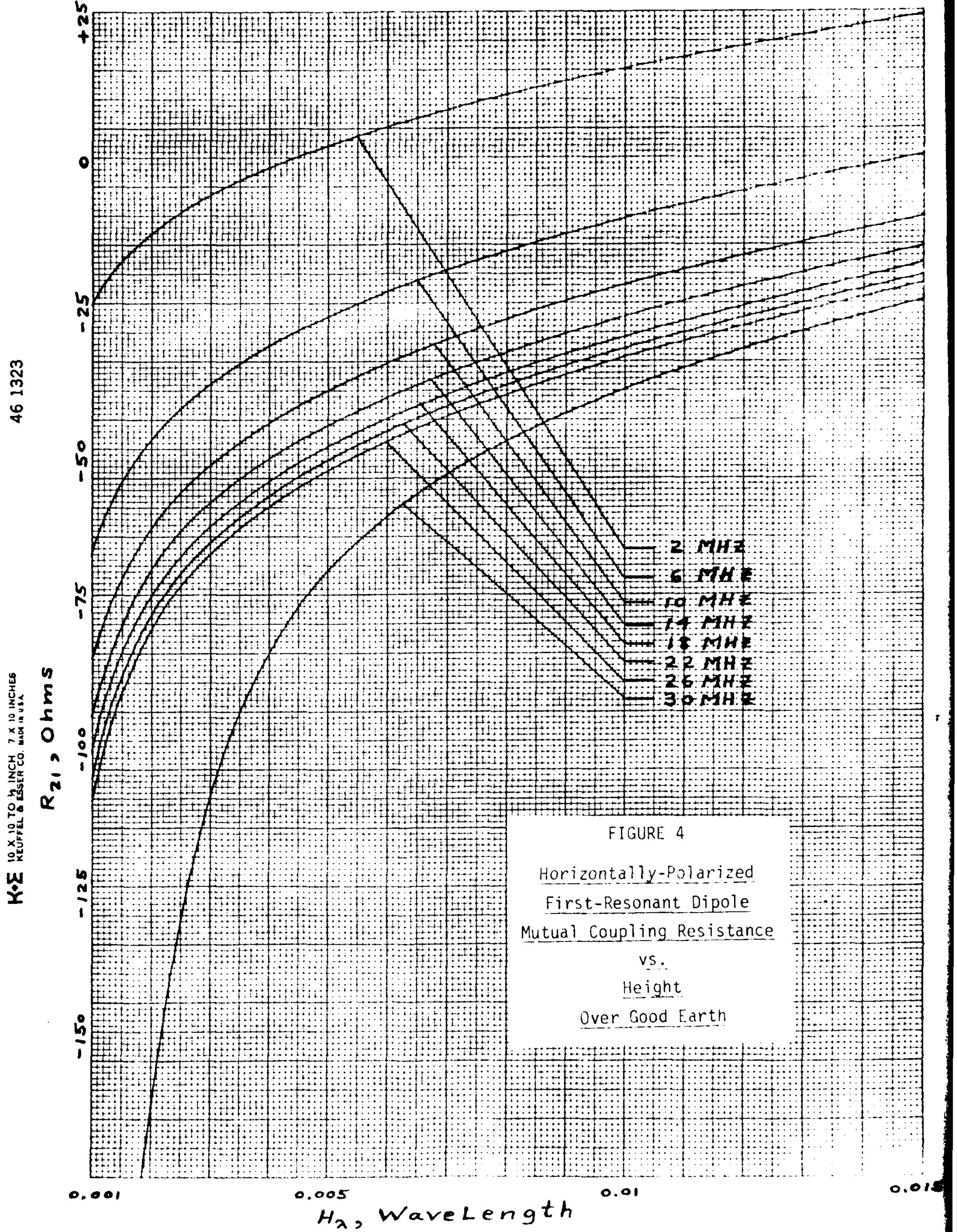


FIGURE 4

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Good Earth

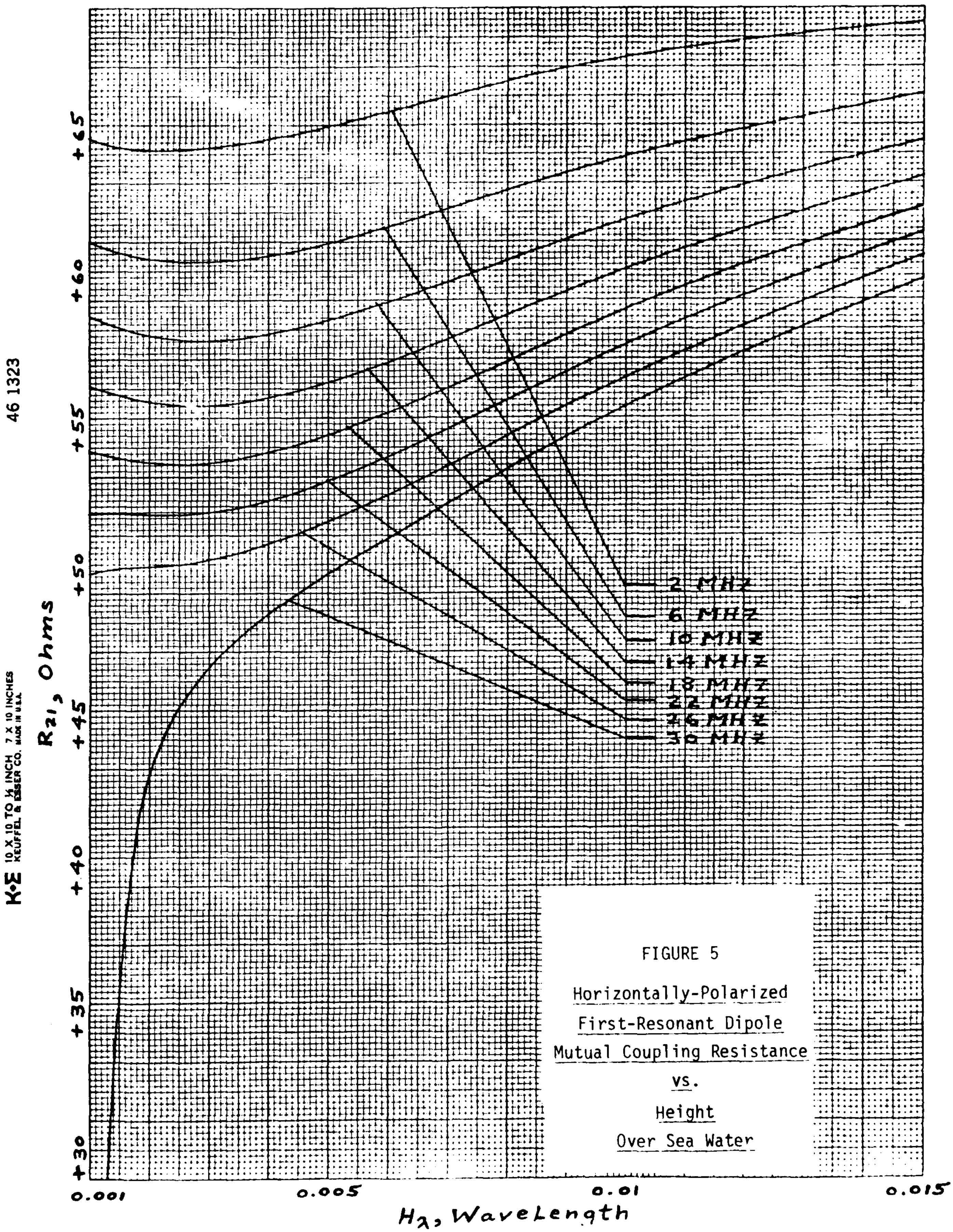


FIGURE 5

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Sea Water

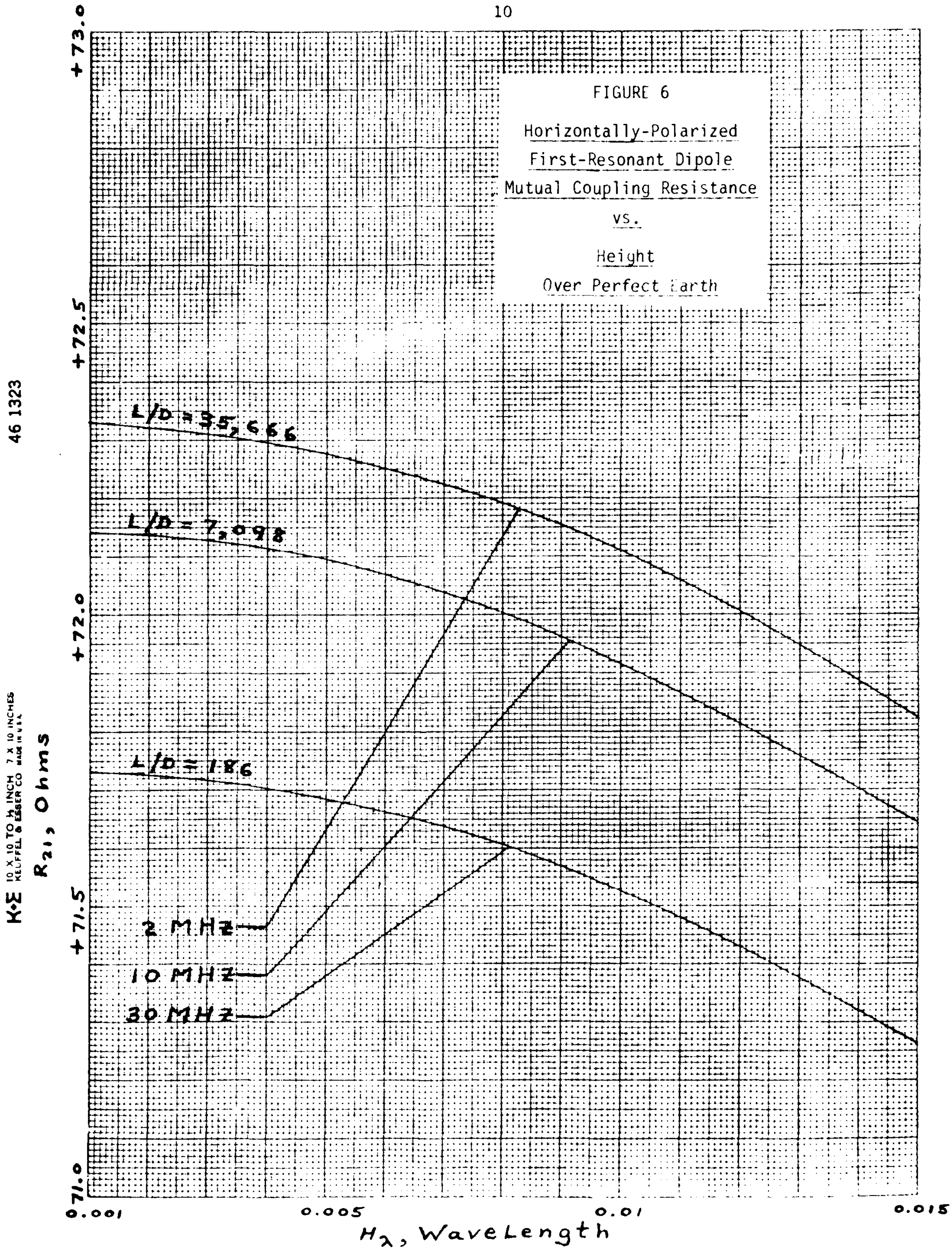


FIGURE 6
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Perfect Earth
L/D = 35,666
L/D = 7,098
L/D = 186
2 MHz
10 MHz
30 MHz
+73.0
+72.5
+72.0
+71.5
71.0
R_{21}, Ohms
0.001
0.005
0.01
0.015
H_λ, WaveLength
46 1323
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

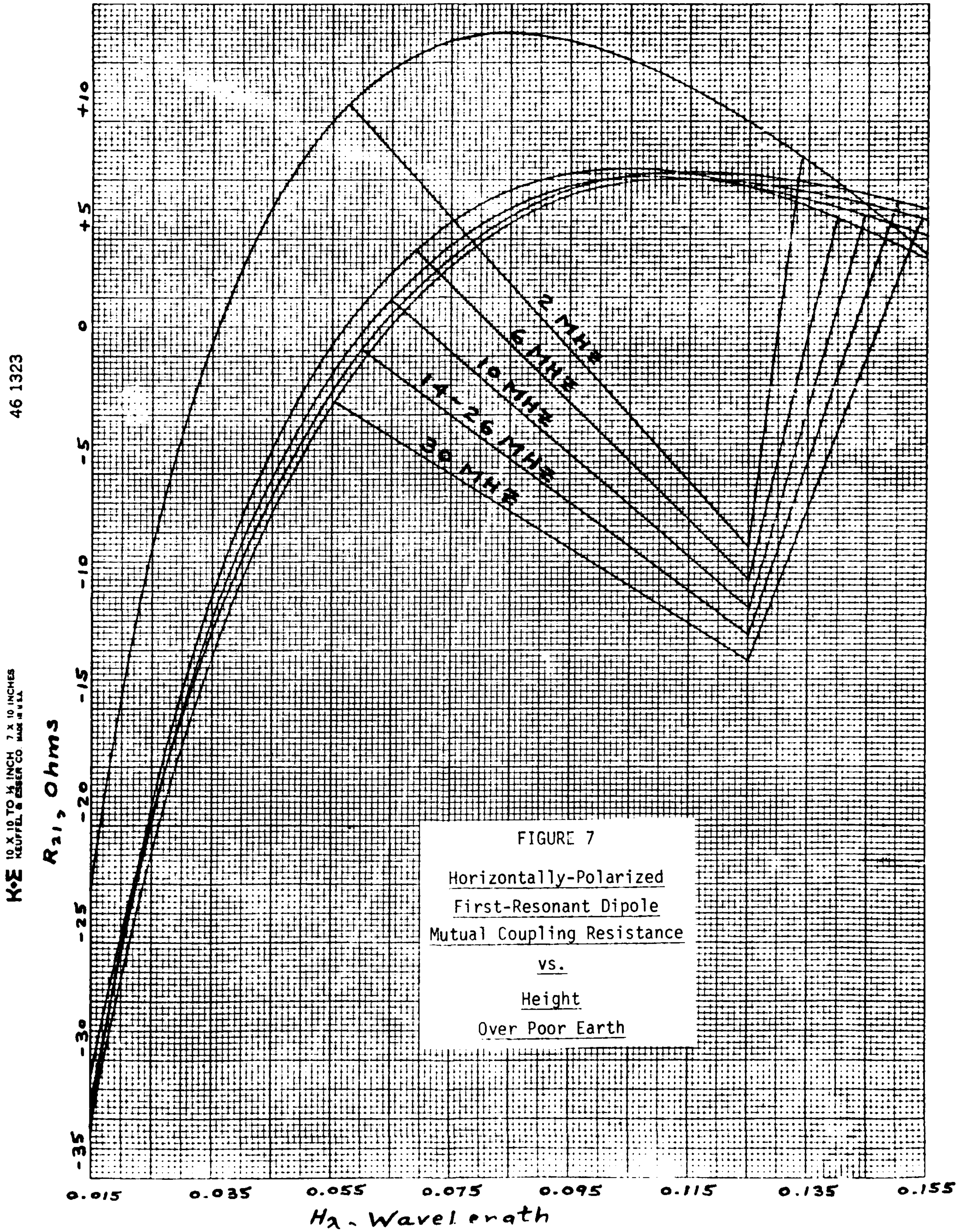


FIGURE 7

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Poor Earth

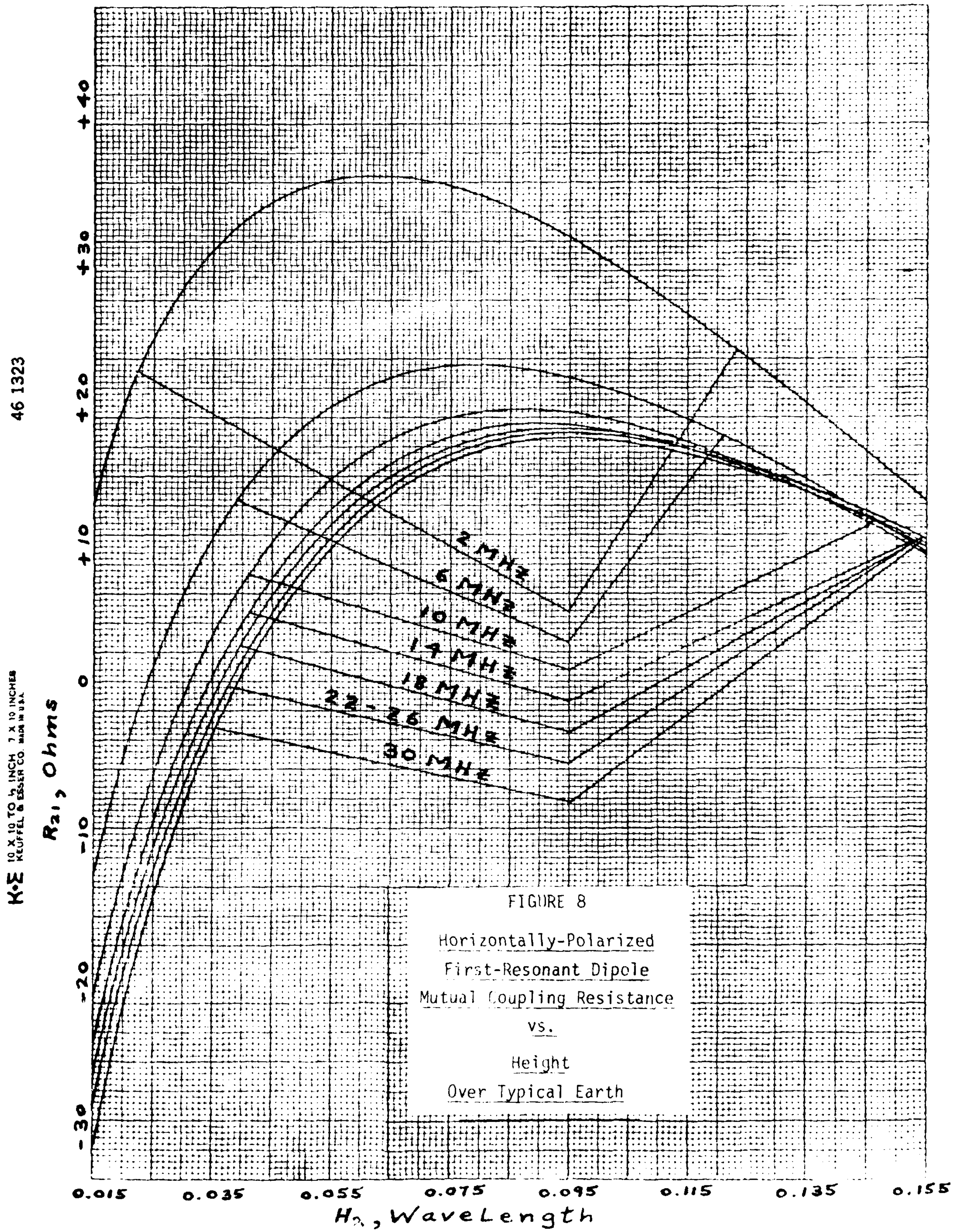


FIGURE 8

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Typical Earth

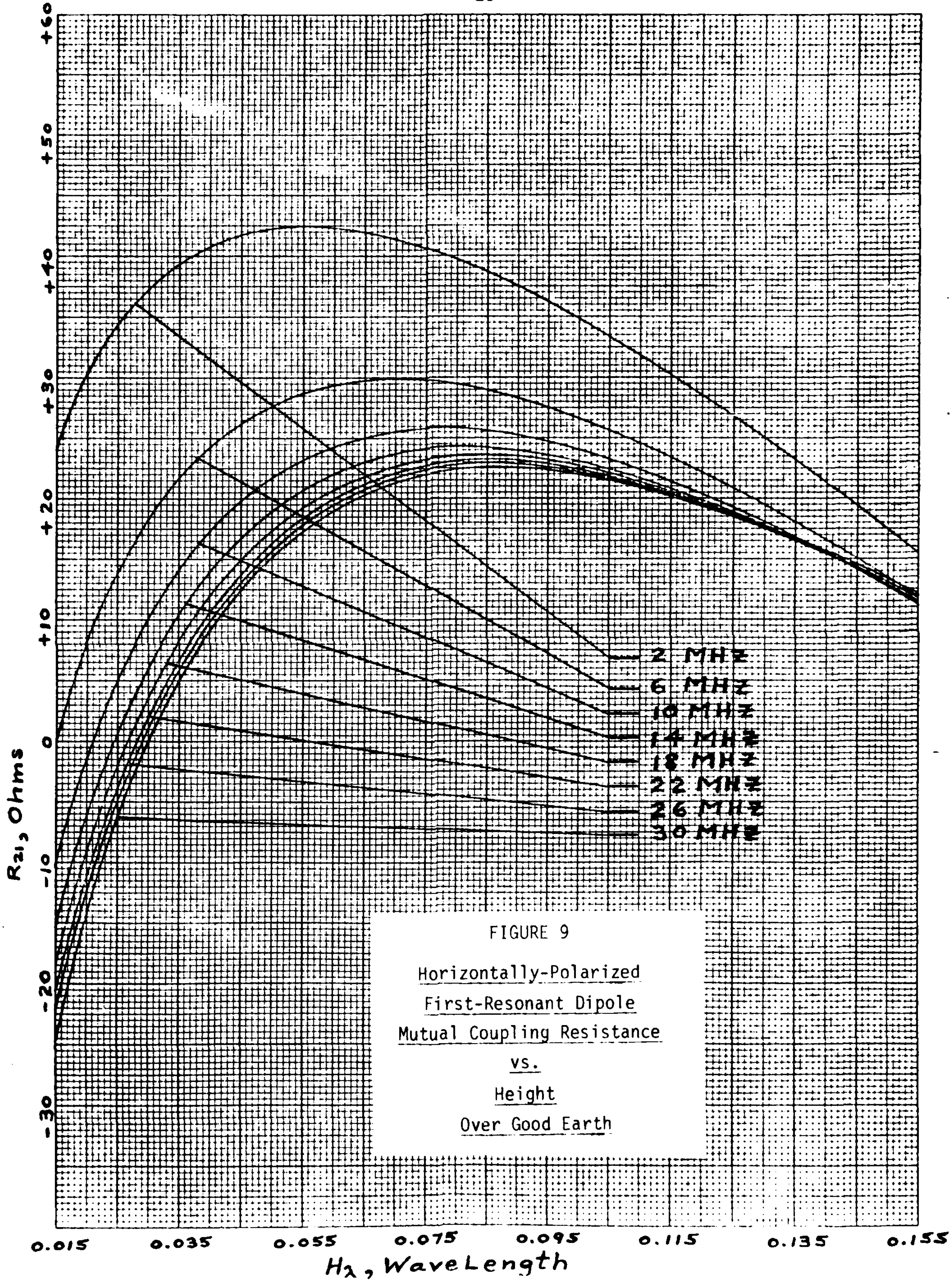


FIGURE 9

Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Good Earth

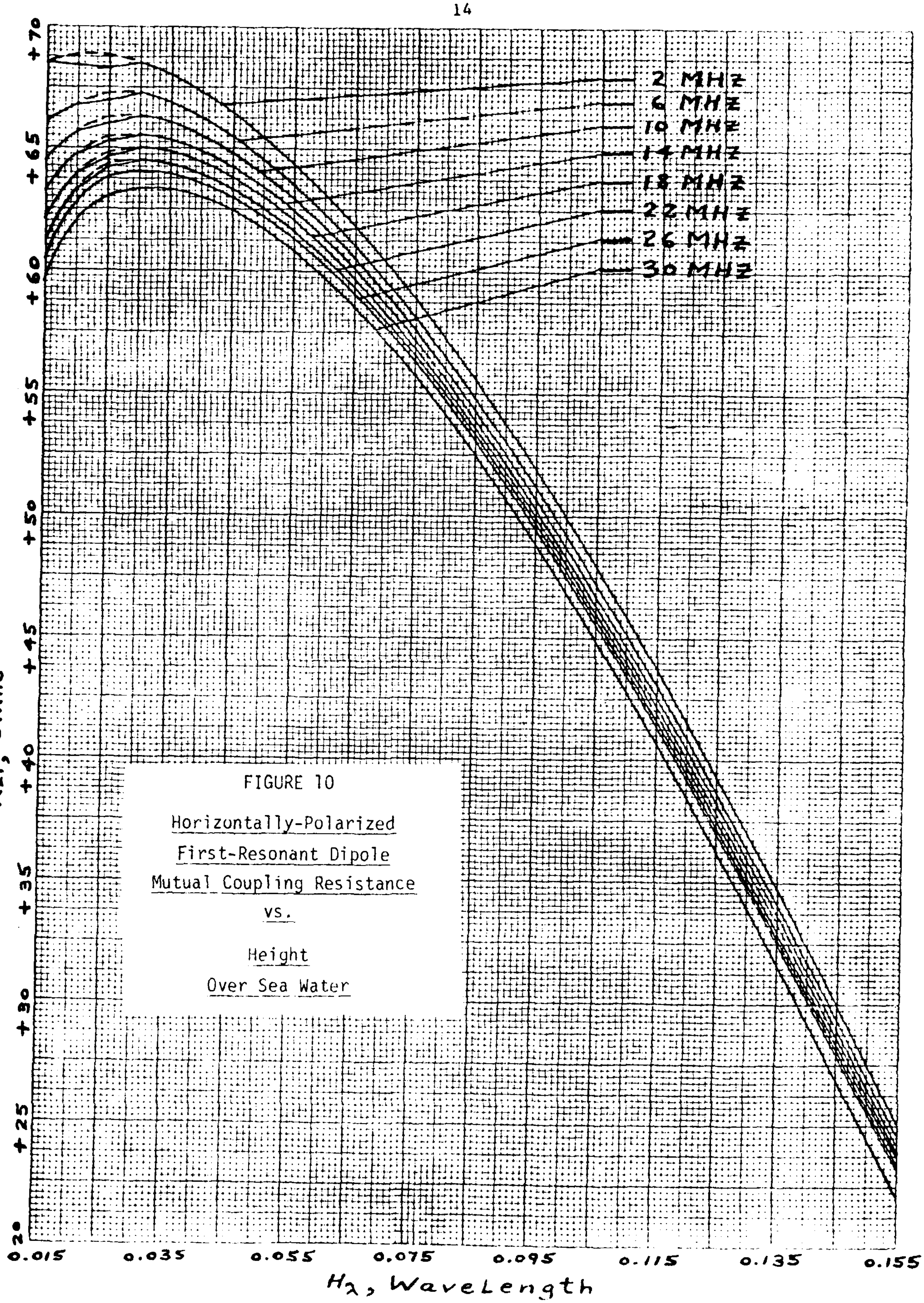


FIGURE 10

Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Sea Water

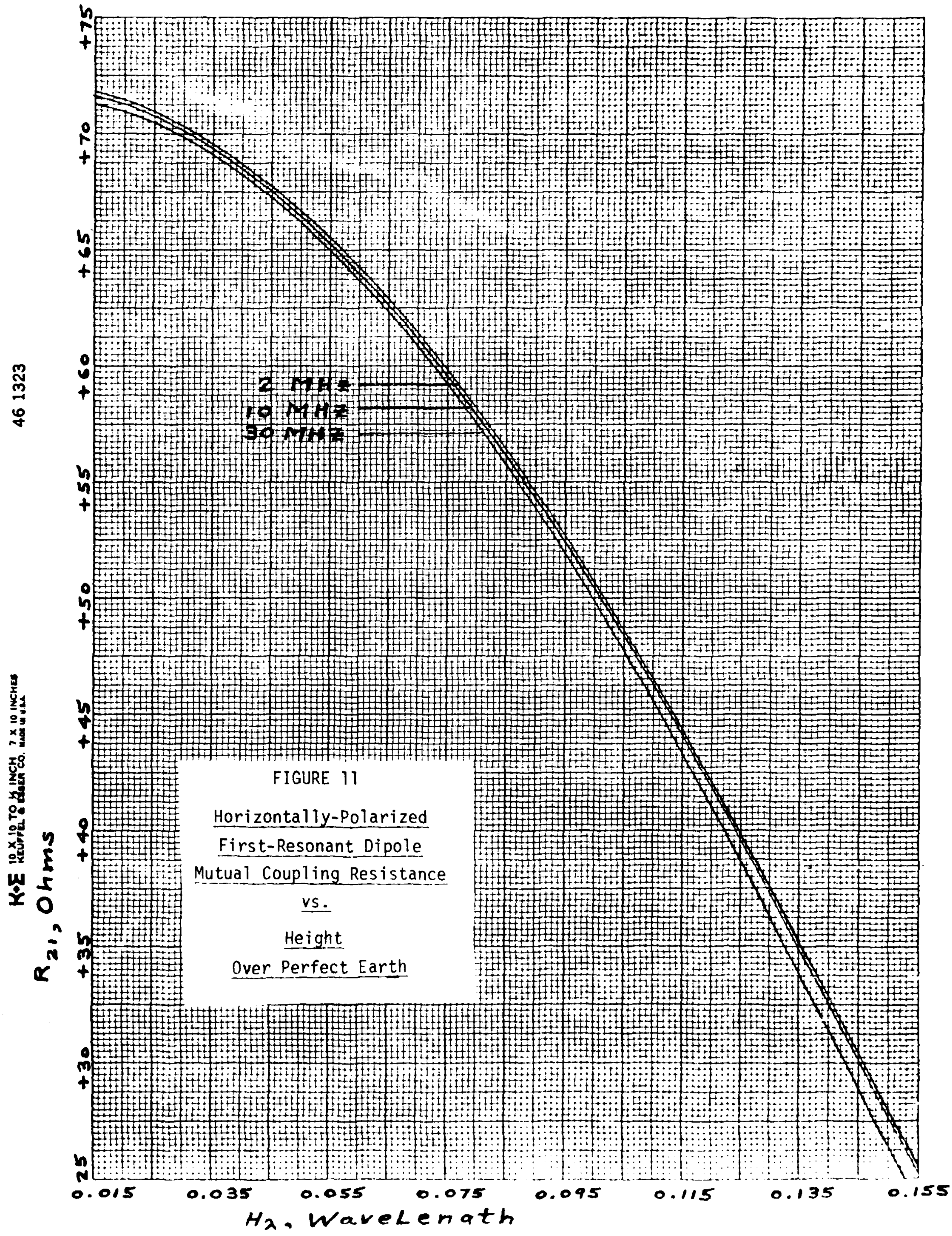


FIGURE 11

Horizontally-Polarized First-Resonant Dipole Mutual Coupling Resistance vs. Height Over Perfect Earth

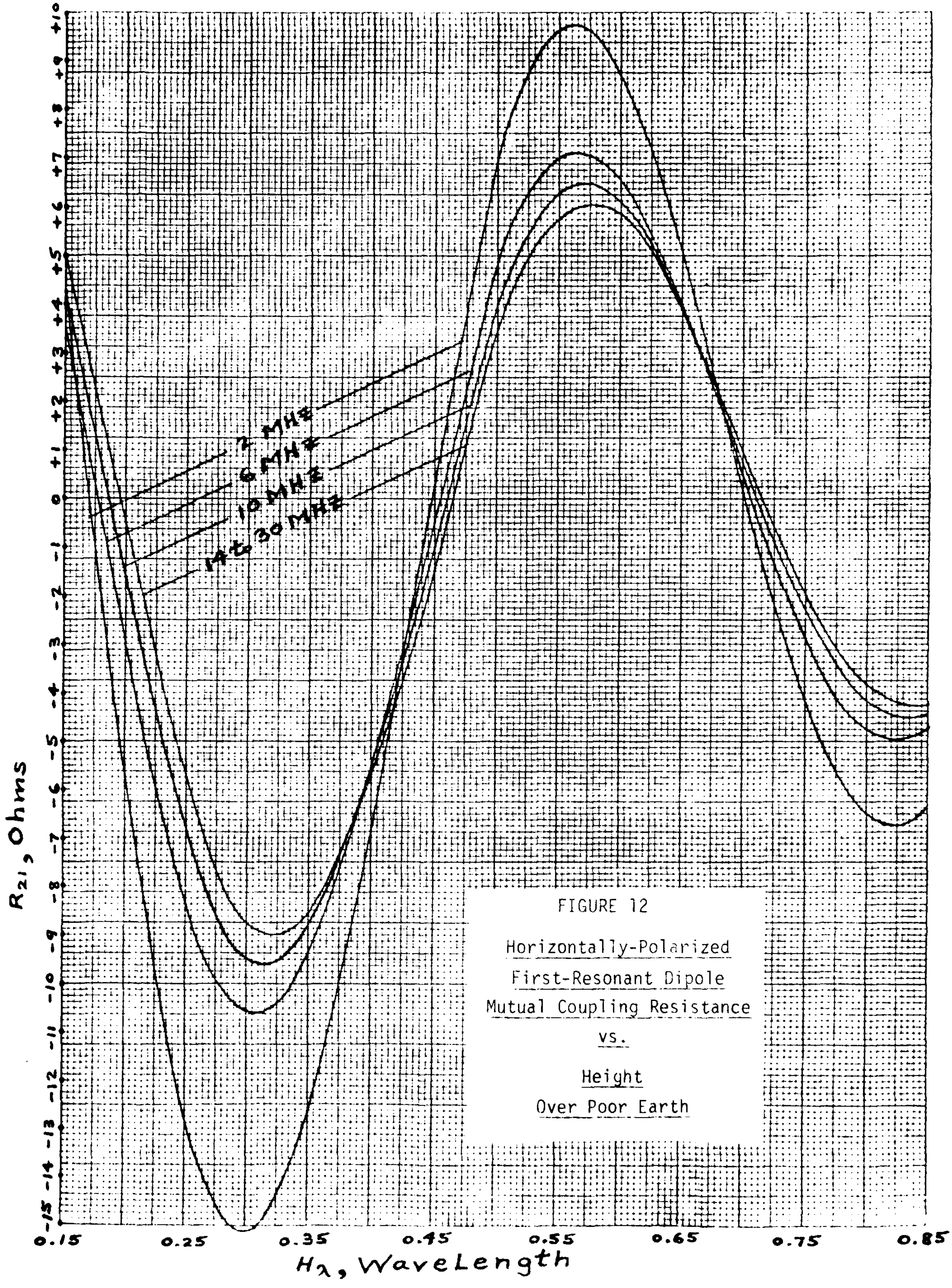


FIGURE 12

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Poor Earth

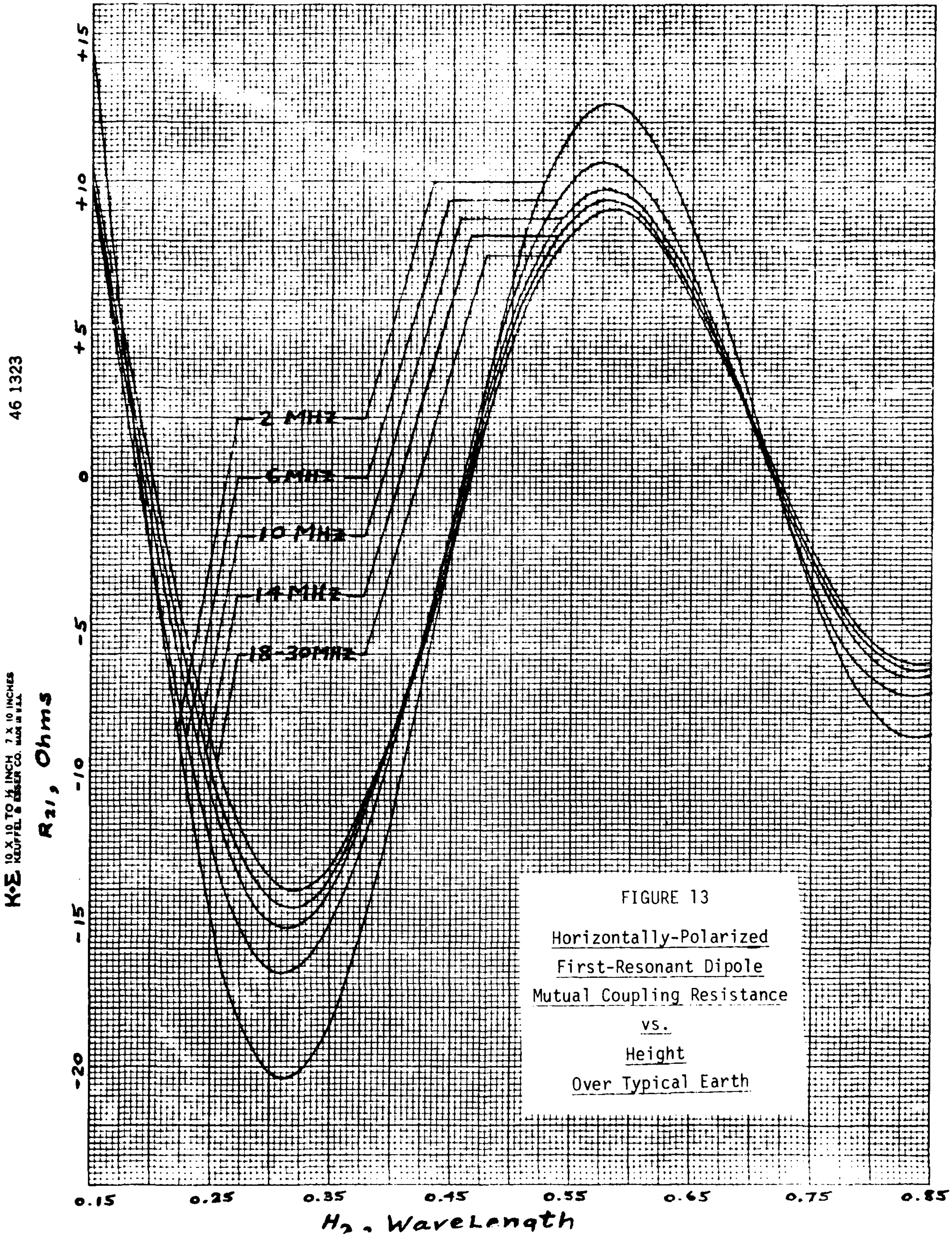


FIGURE 13

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Typical Earth

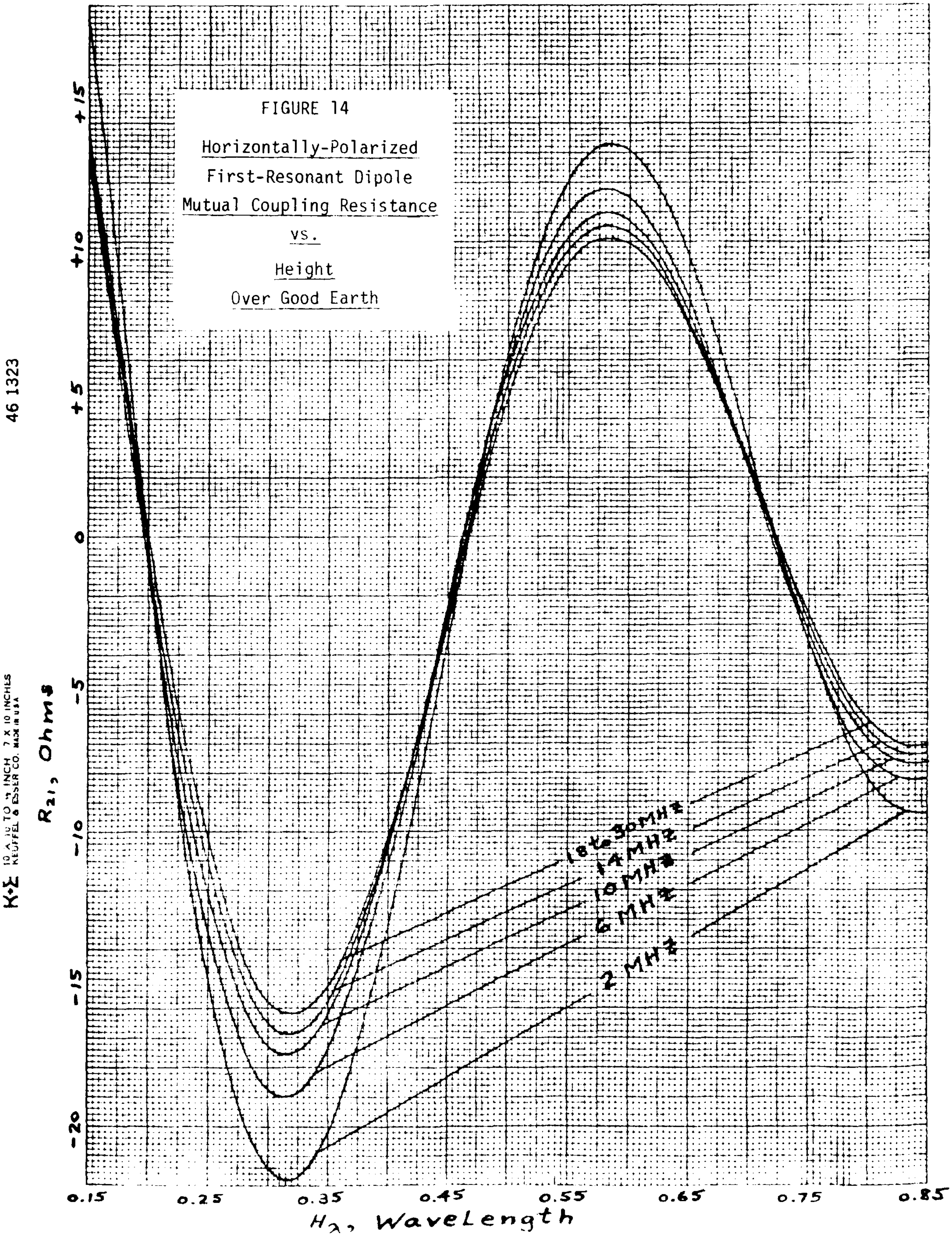


FIGURE 14
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Good Earth
+15
+10
+5
0
-5
-10
-15
-20
R_{21}, Ohms
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
H_λ, Wavelength
18 to 30 MHz
14 MHz
10 MHz
6 MHz
2 MHz

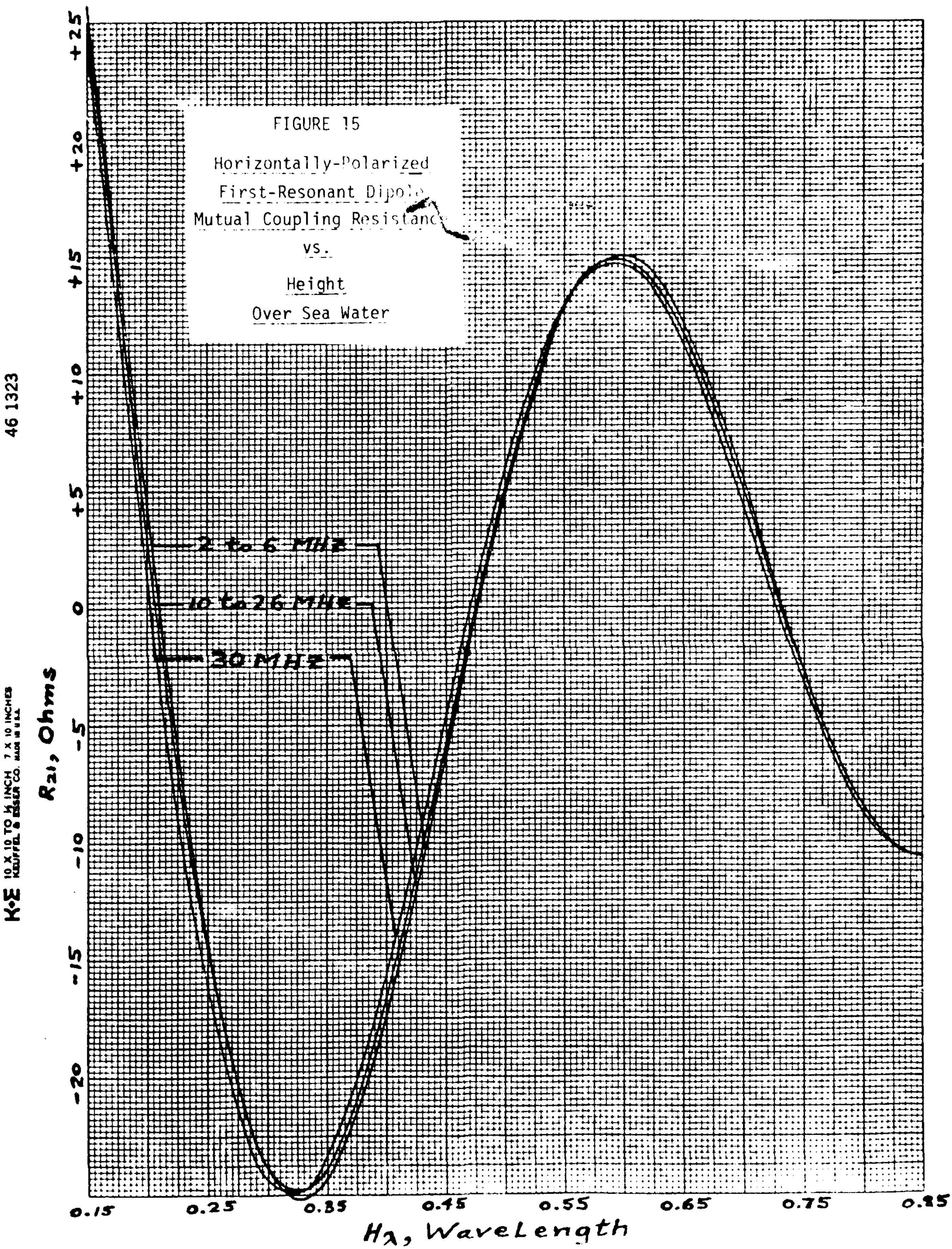


FIGURE 15
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Sea Water
2 to 6 MHz
10 to 26 MHz
30 MHz
+25
+20
+15
+10
+5
0
-5
-10
-15
-20
R_{21}, Ohms
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
H_λ, Wavelength
46 1323
K+E 10 X 10 TO ½ INCH 7 X 10 INCHES
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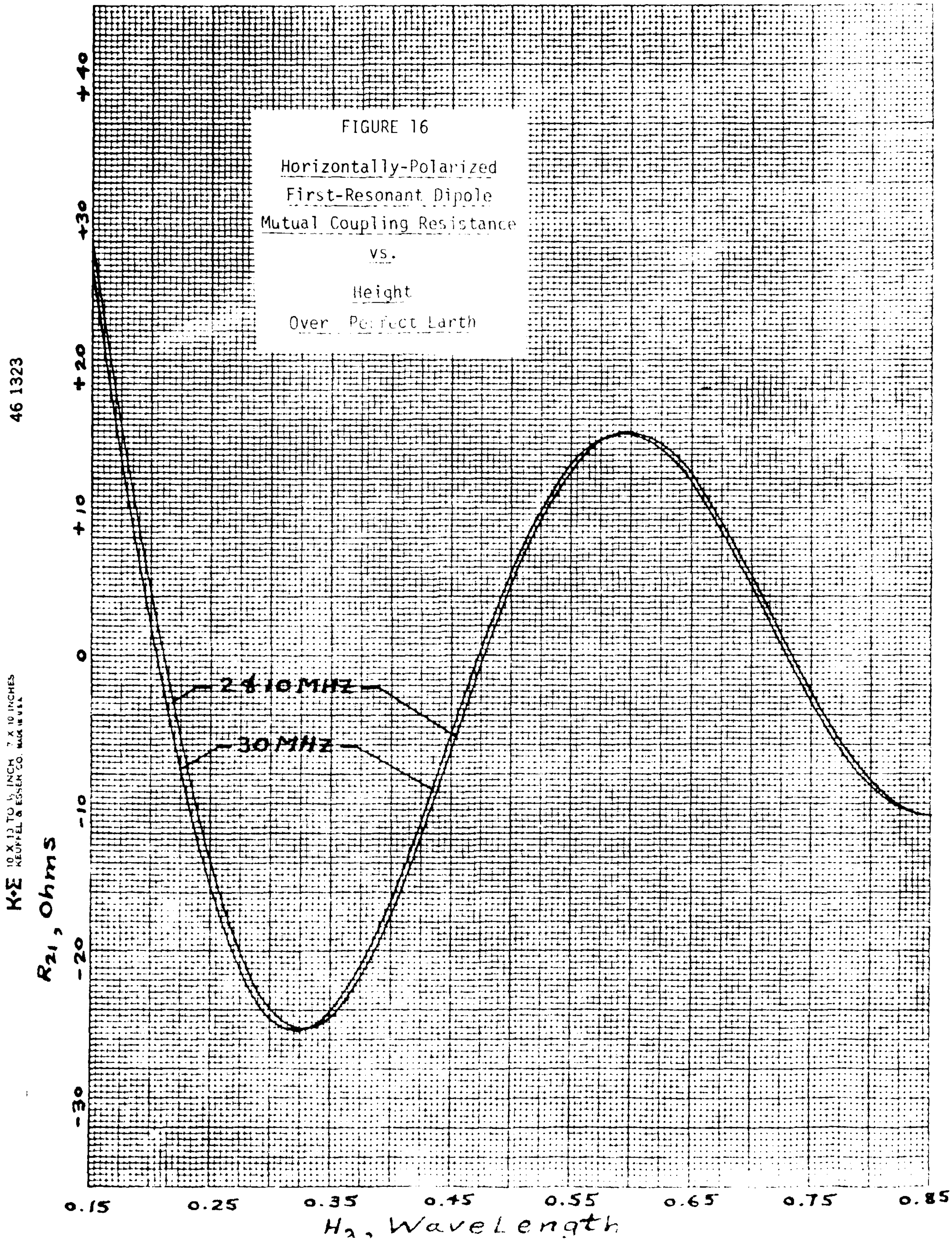


FIGURE 16

Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Perfect Earth

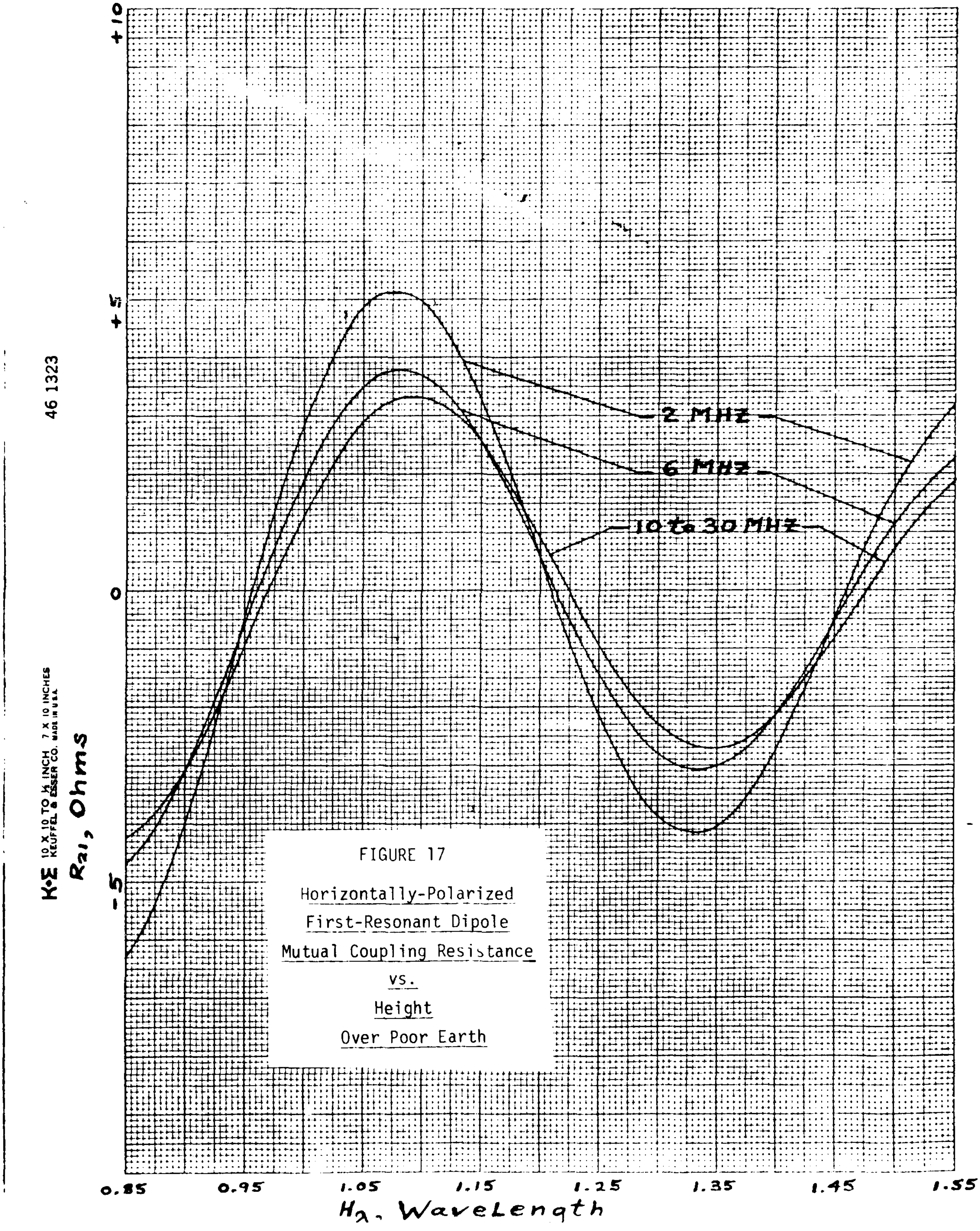


FIGURE 17

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Resistance

vs.

Height

Over Poor Earth

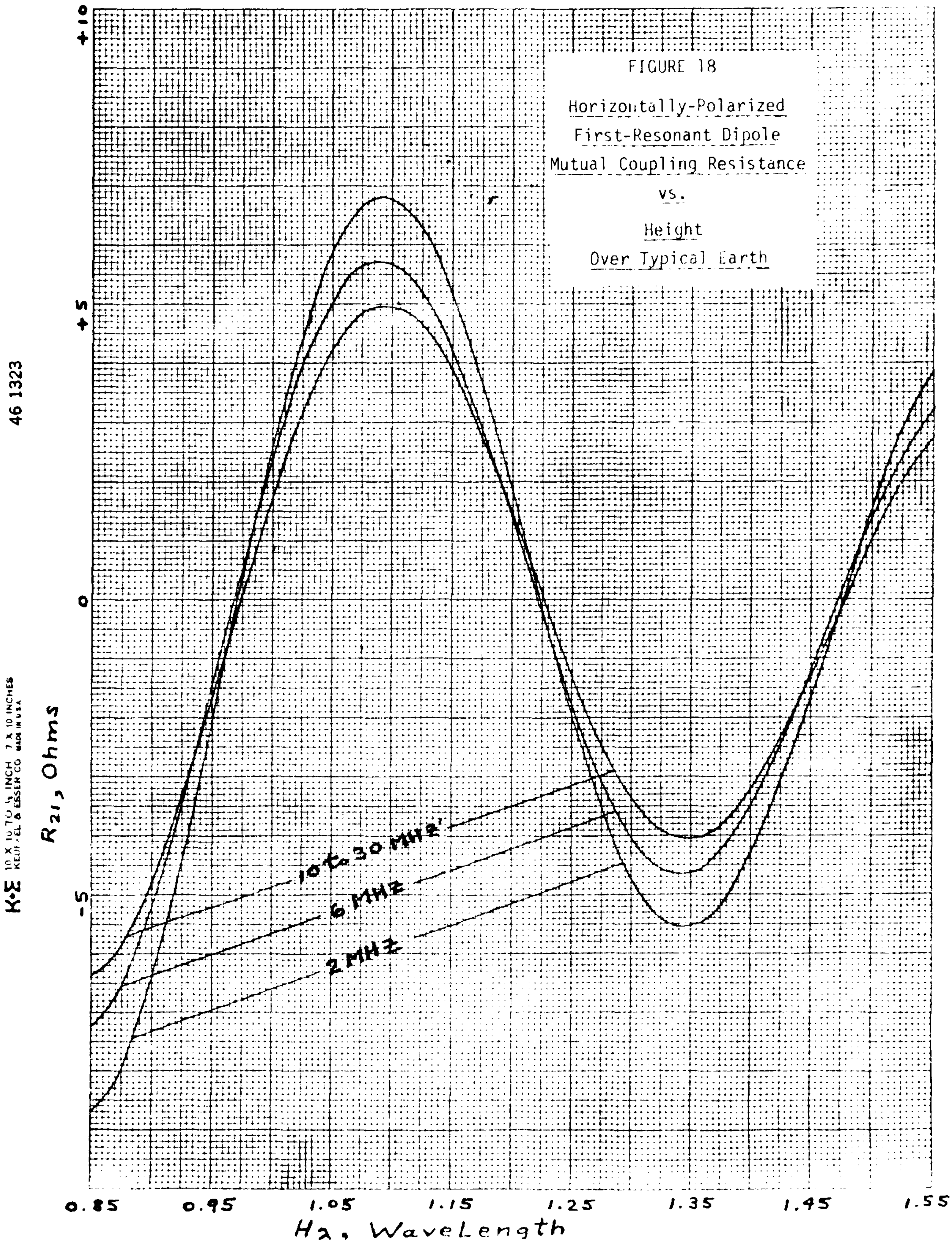


FIGURE 18
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Typical Earth
+10
+5
0
-5
R_{21}, Ohms
10 to 30 MHz
6 MHz
2 MHz
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.55
H_λ, WaveLength
K·E 10 X 10 TO ½ INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1323

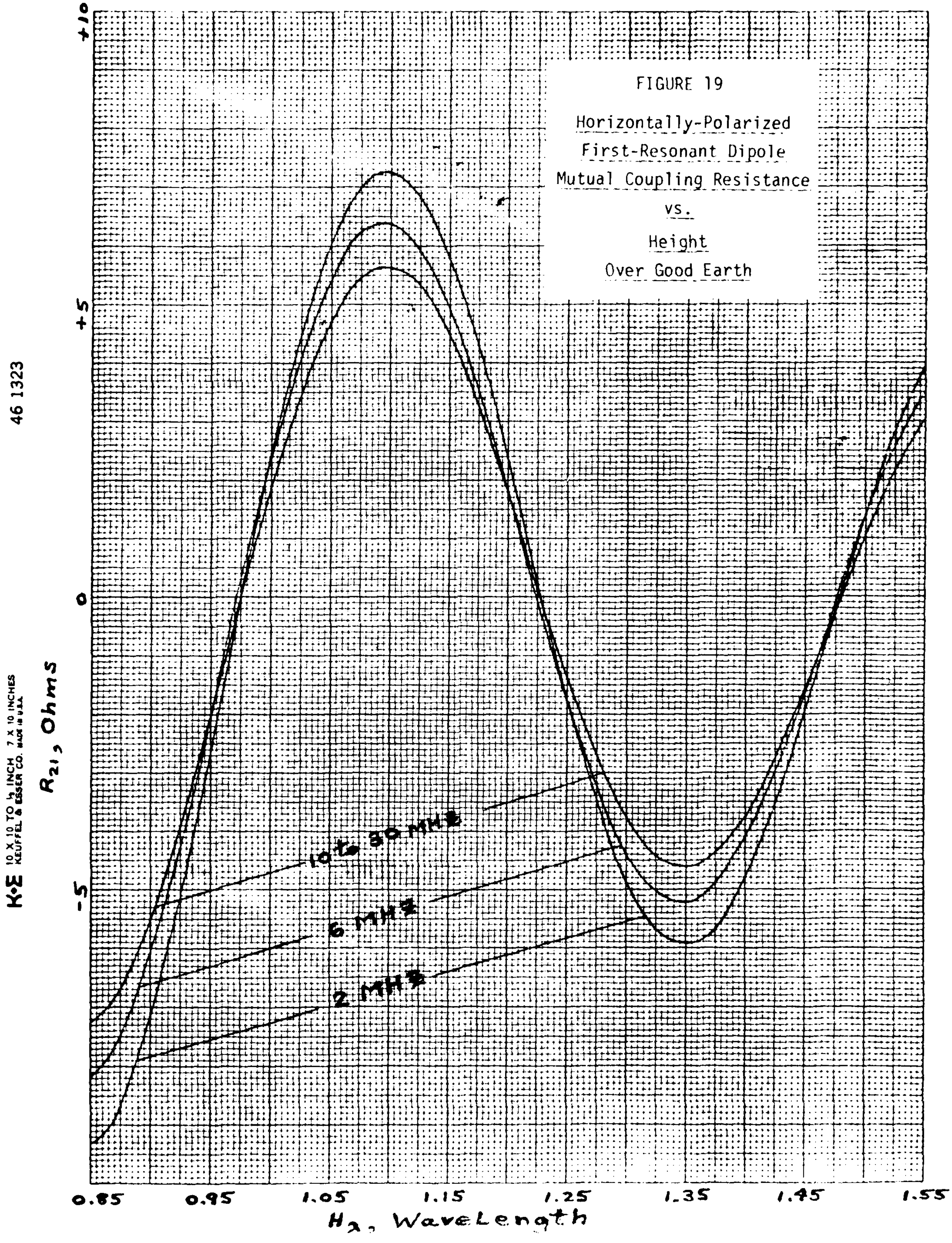


FIGURE 19
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Good Earth
+10
+5
0
-5
R_{21}, Ohms
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.55
H_λ, WaveLength
10 to 30 MHz
6 MHz
2 MHz
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1323

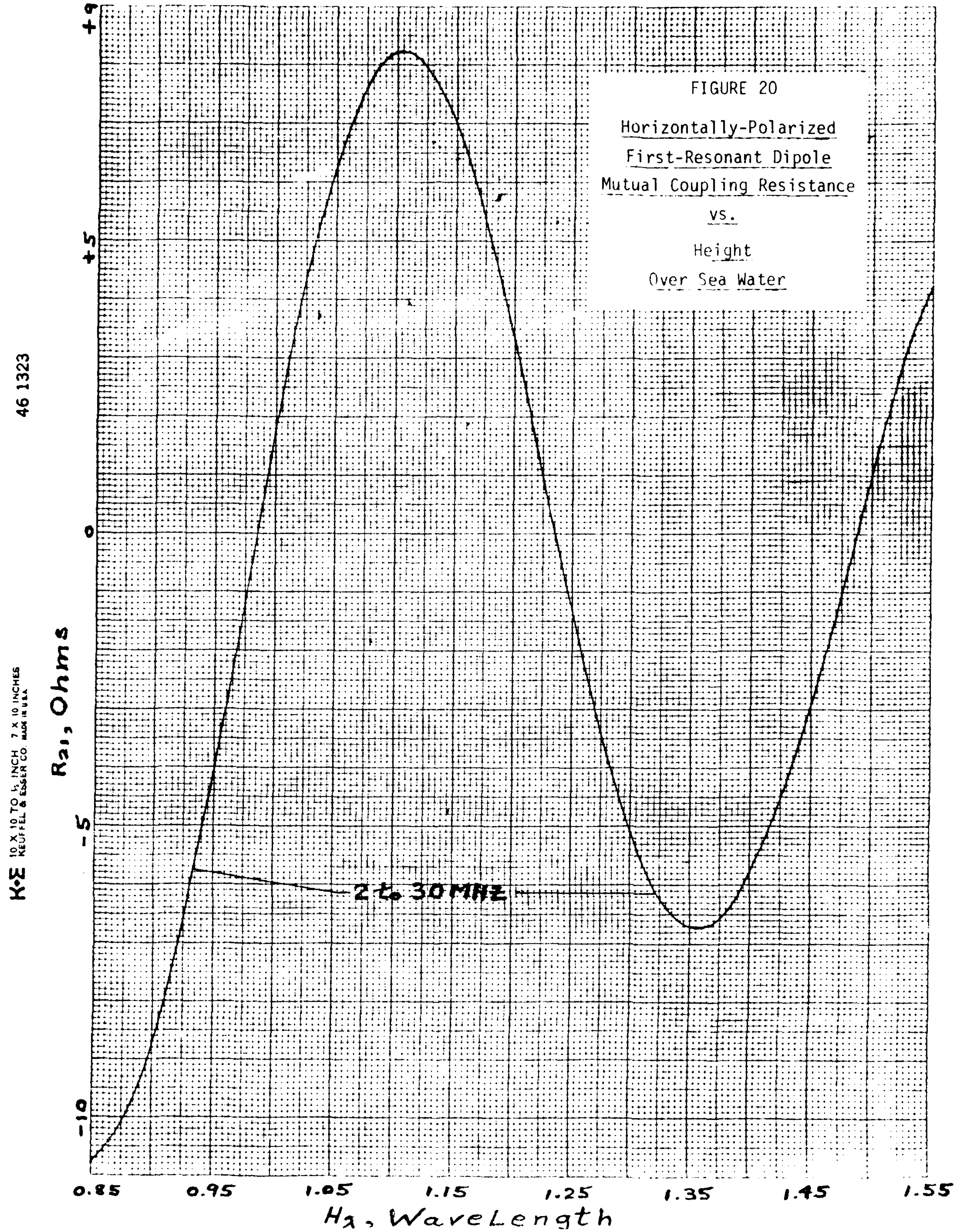


FIGURE 20
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Sea Water
+9
+5
0
-5
-10
R_{21}, Ohms
2 to 30 MHz
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.55
H_λ, WaveLength
K+E 10 X 10 TO ½ INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1323

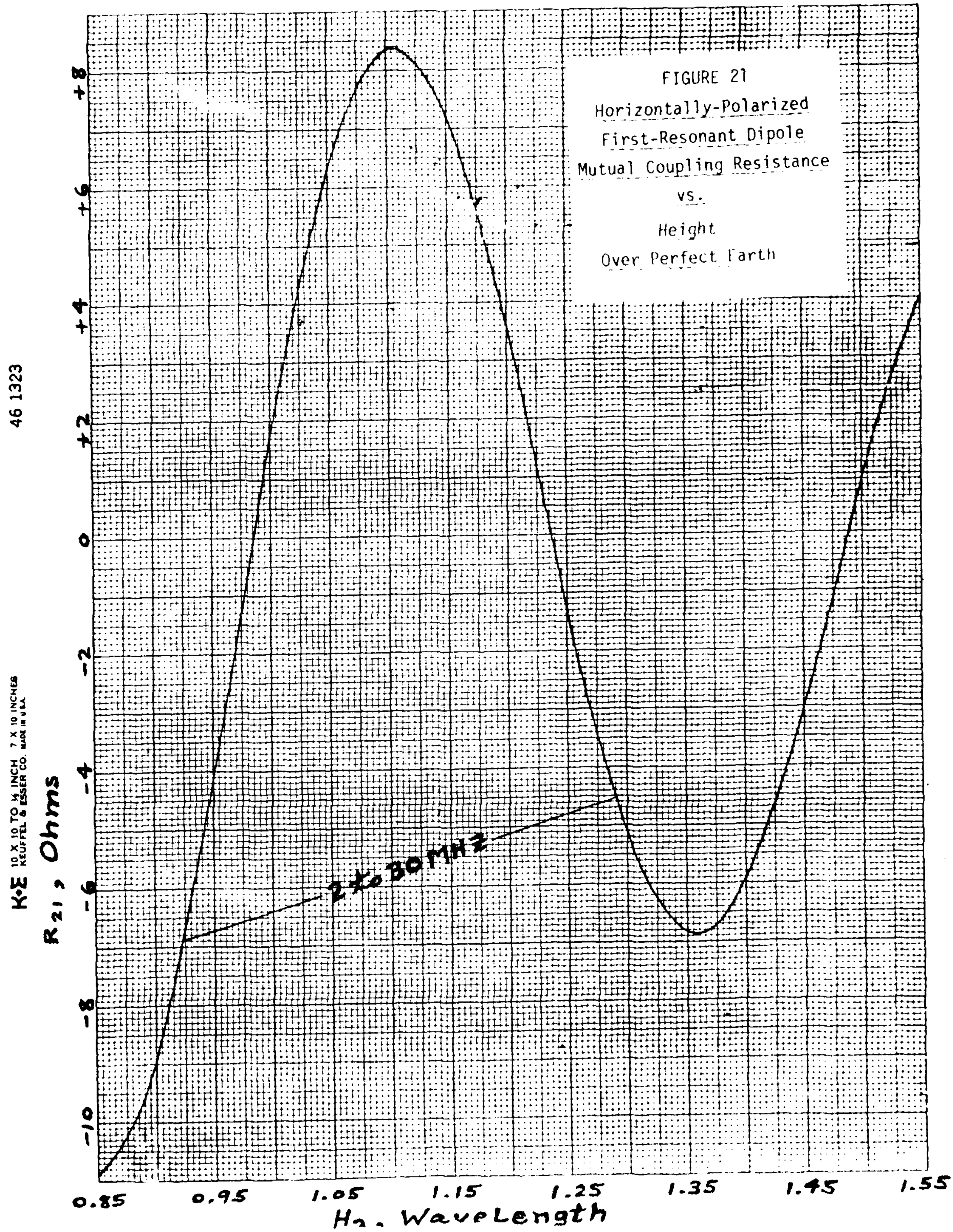


FIGURE 21
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Perfect Earth

where a tubing diameter of 1.0 inch was used. Equation 4 of reference 4 was used, as discussed in the introduction, to obtain first resonant L/D ratios which are plotted on Figure 52 in Summa · section, and shown on Figure 6 at 2, 10, and 30 MHz.

When the L/D ratios shown on Figure 6 are used in equation 9 of reference 4, solutions for R_{11} are 0.06 ohms less than NEC solutions at 2.0 MHz, 0.03 ohms greater than NEC solutions at 10.0 MHz, and 0.03 ohms greater than NEC solutions at 30.0 MHz. The difference between the NEC solution curves shown on Figure 6 is a function of dipole first-resonant lengths of $0.488386\lambda_0$ at 2.0 MHz, $0.485980\lambda_0$ at 10.0 MHz, and $0.473683\lambda_0$ at 30.0 MHz.

The results plotted on Figure 10 show that NEC solutions are not correct when the dipole height is $0.015 \leq H_\lambda \leq 0.03$ wavelength over sea water and the frequency is below 26 MHz. Surprisingly, this height range is well within the RCM limit discussed in the Introduction leading to equation 1 and Figure 1. Since the subroutine gives reasonable solutions when other combinations of earth electrical properties, frequency, and height are used, the error appears to be philosophical.

III. HORIZONTALLY-POLARIZED MUTUAL REACTANCE.

The mutual reactance, X_{21}, results are plotted on Figures 22-26, 27-31, 32-36, and 37-41 for height, H_λ, intervals of 0.001-0.015, 0.015-0.155, 0.15-0.85, and 0.85-1.55 wavelengths, respectively. Thus, at each height interval there are 5 graphs, one for each defined earth, and the frequency or frequency range is plotted on each graph.

With the graphs so arranged, some degree of earth interpolation is enhanced. As an example, let the earth's electrical properties be $\varepsilon_r = 10$ and $\sigma = 0.002$ mhos/meter (between poor and typical earth). Using Figures 22 and 23 with $H = 0.01\lambda_0$ and $f = 2.0$ MHz, the solution is $-90.8 < X_{21} < -64.6$ ohms. The NEC solution is -80.7 ohms.

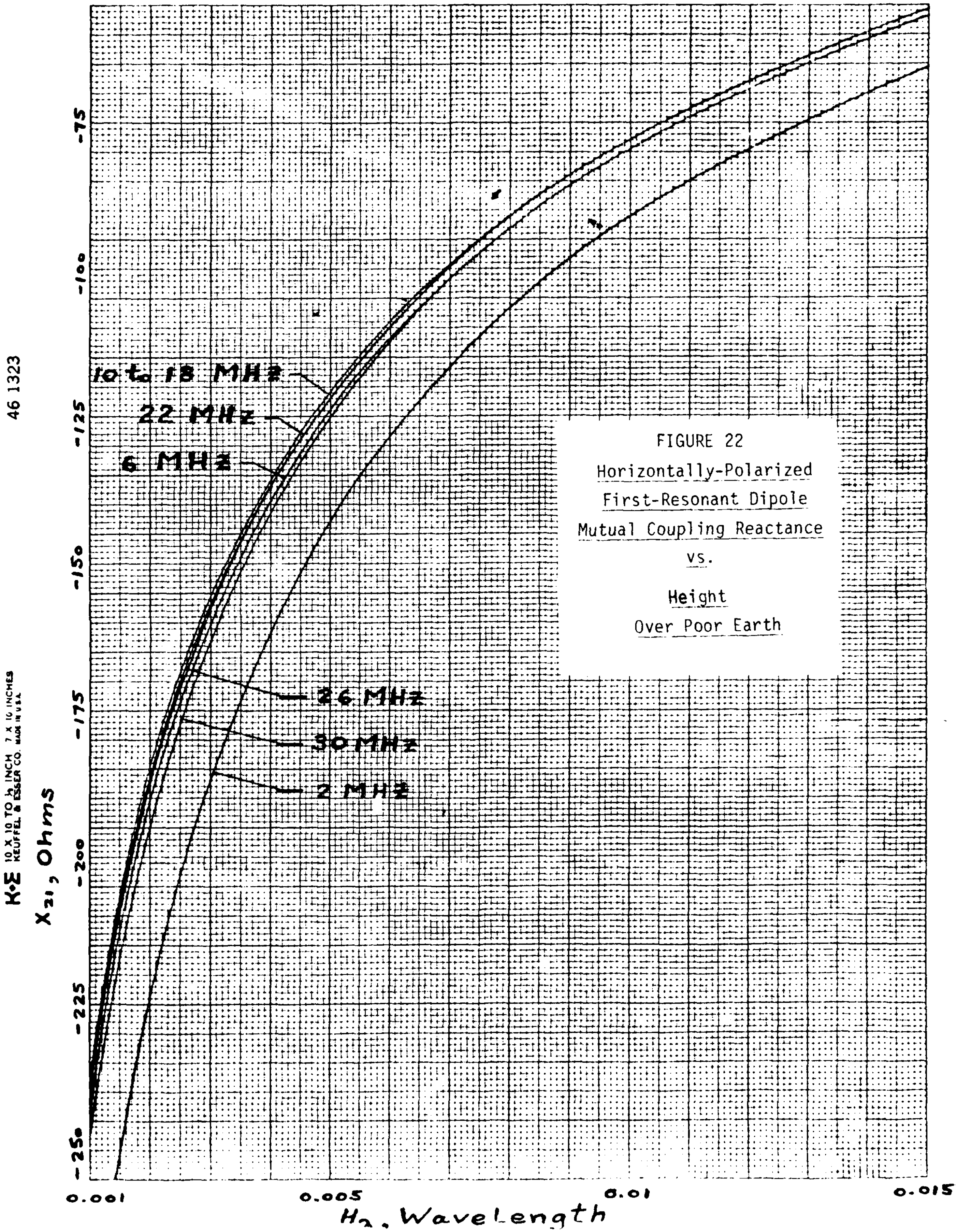


FIGURE 22

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Poor Earth

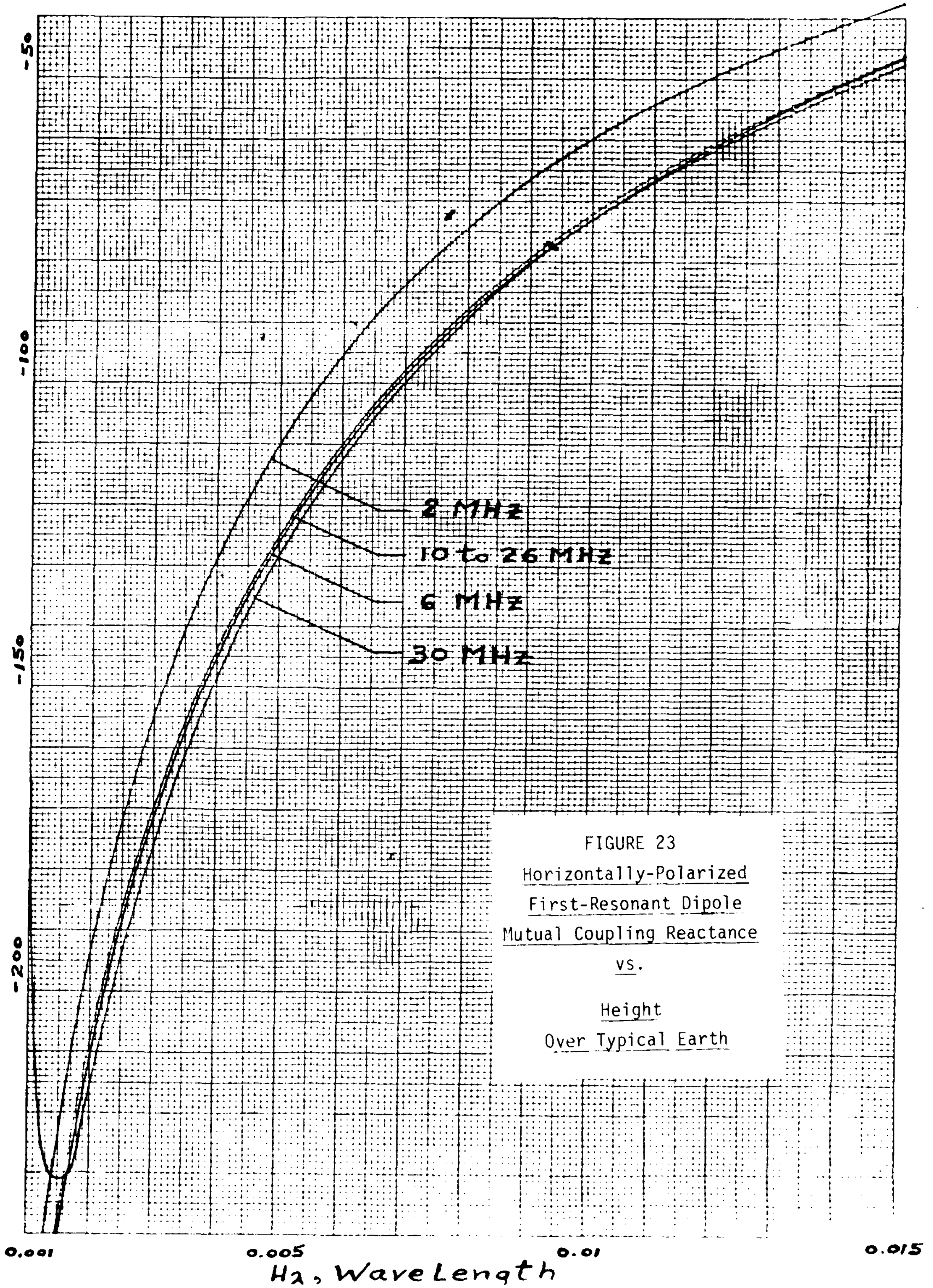


FIGURE 23
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Typical Earth

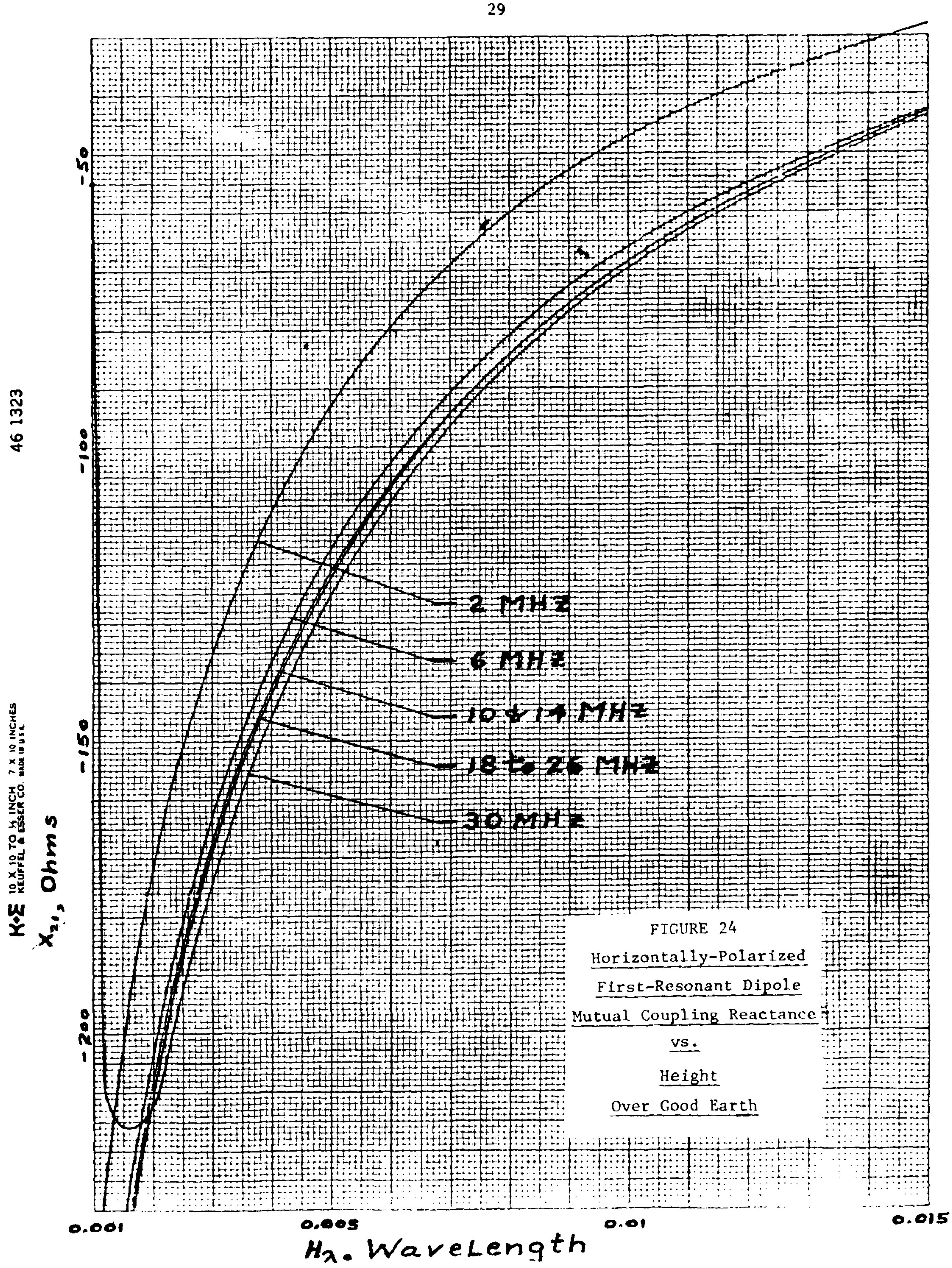


FIGURE 24

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Good Earth

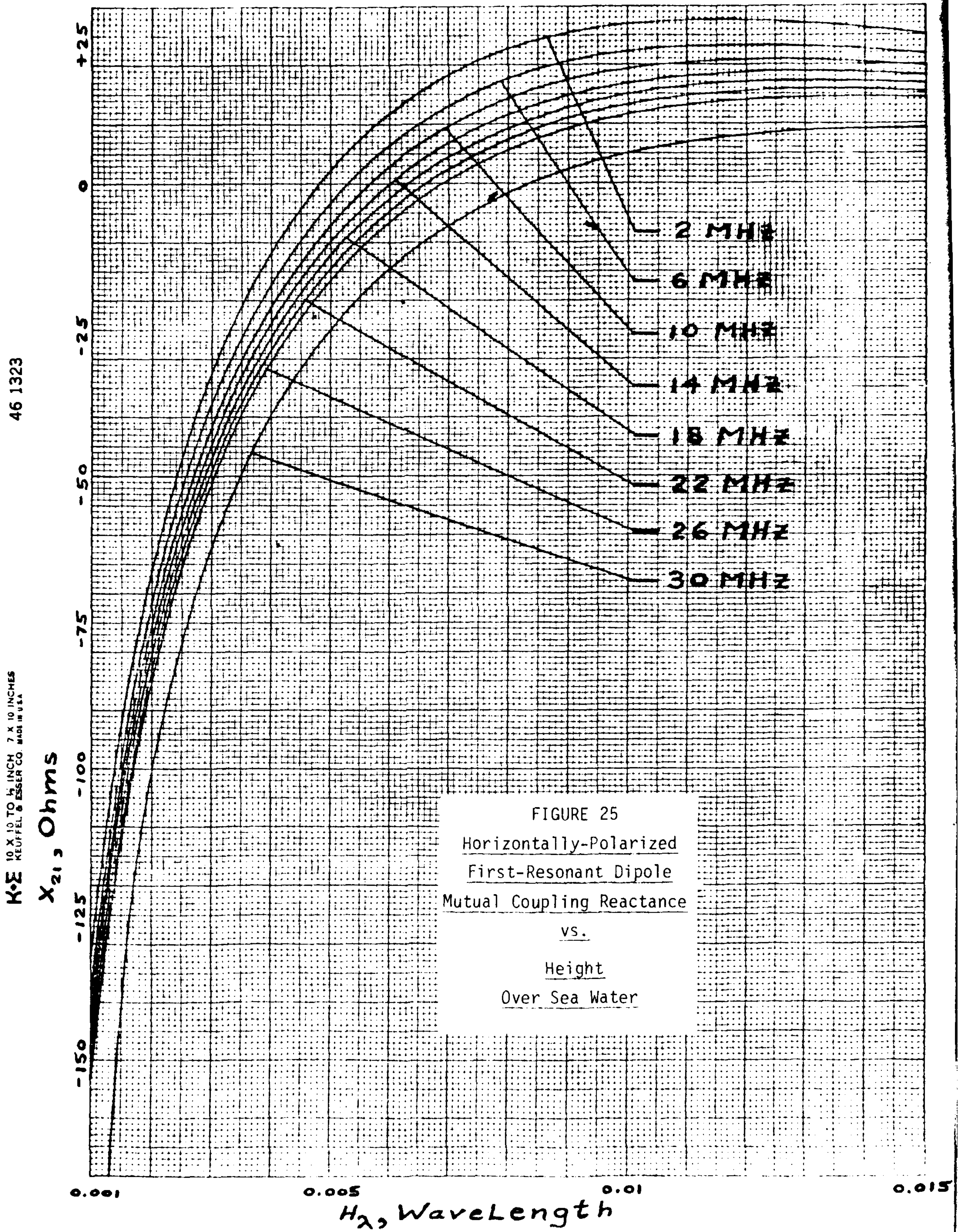


FIGURE 25

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Sea Water

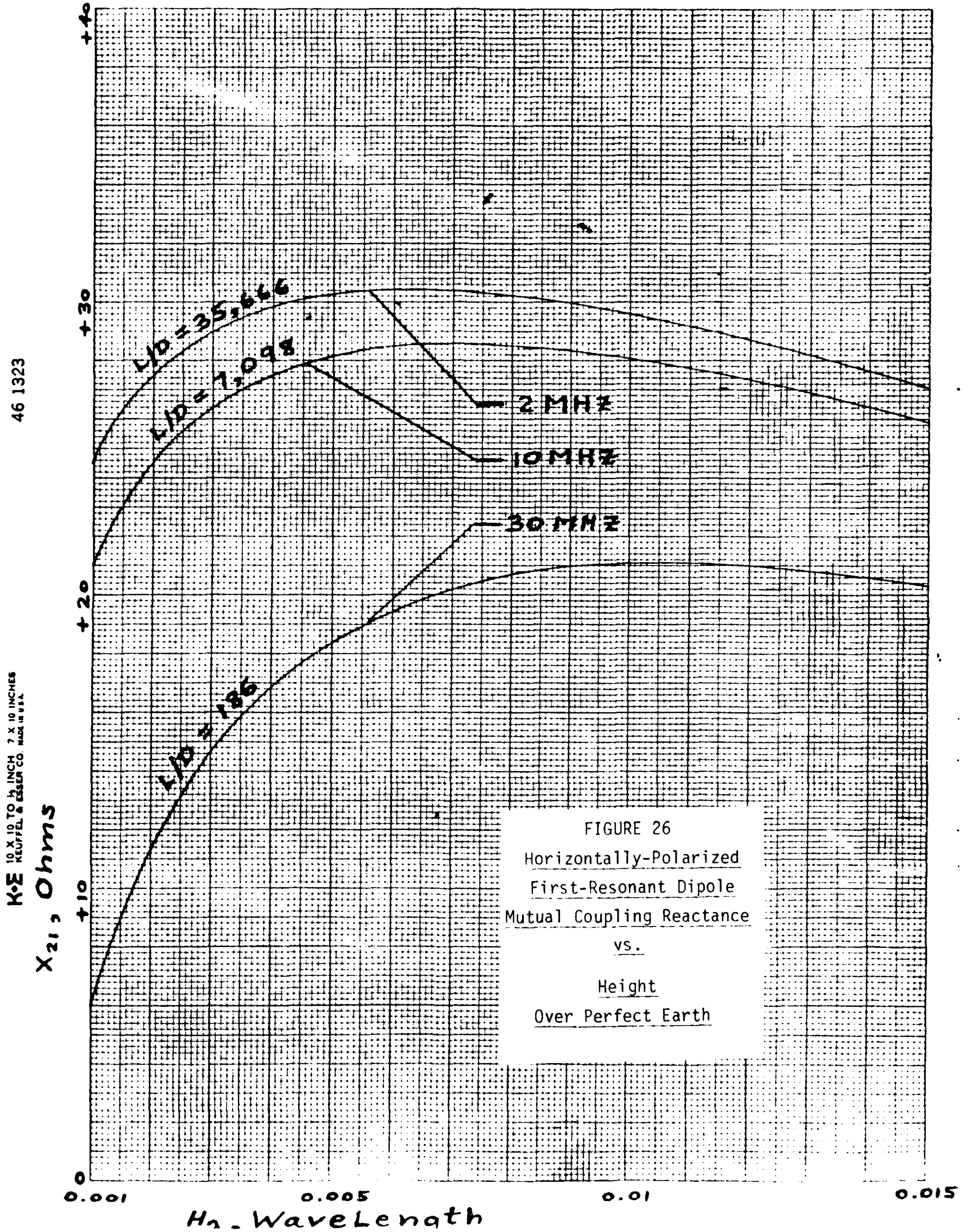


FIGURE 26

Horizontally-Polarized First-Resonant Dipole Mutual Coupling Reactance vs. Height Over Perfect Earth

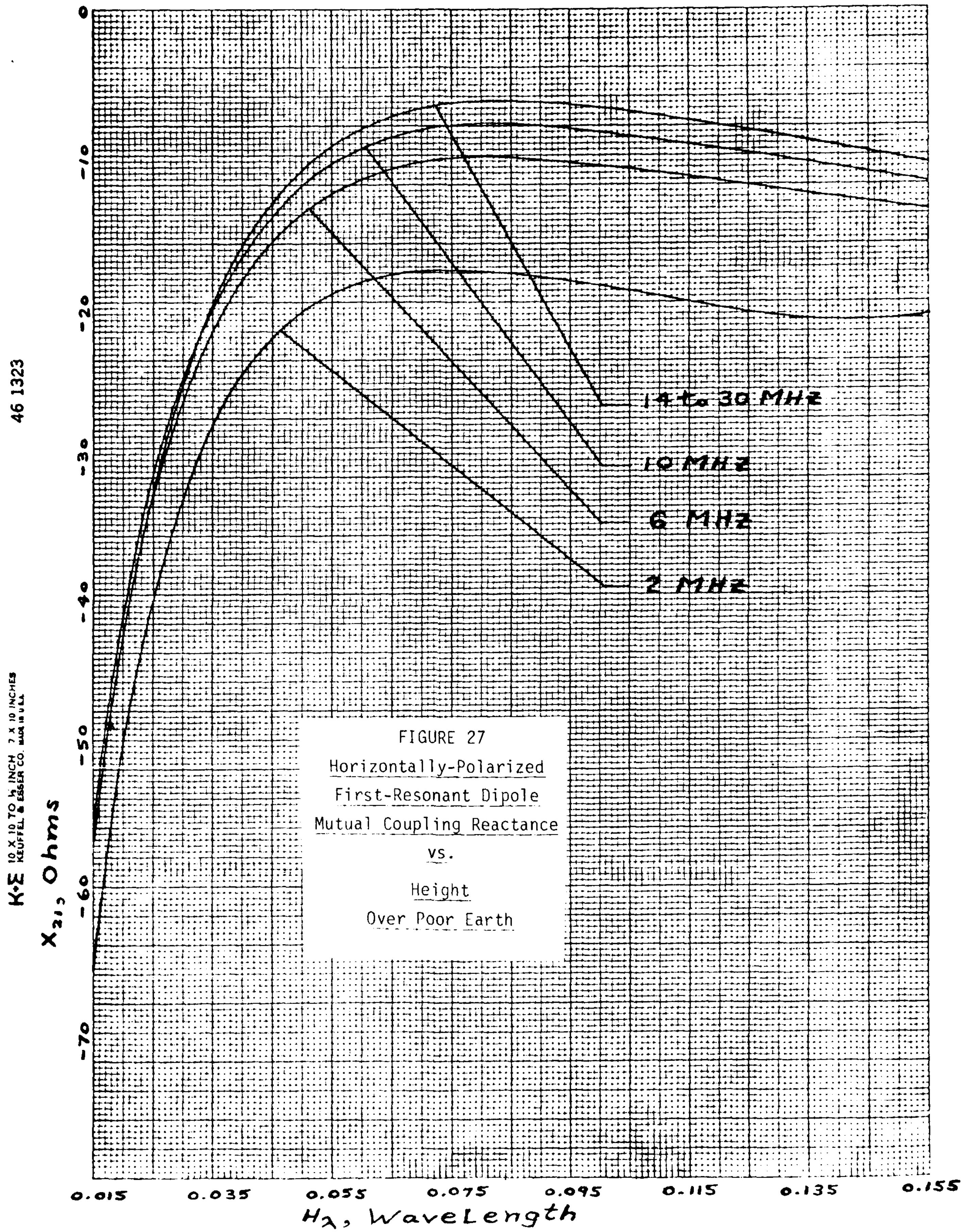


FIGURE 27
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Poor Earth

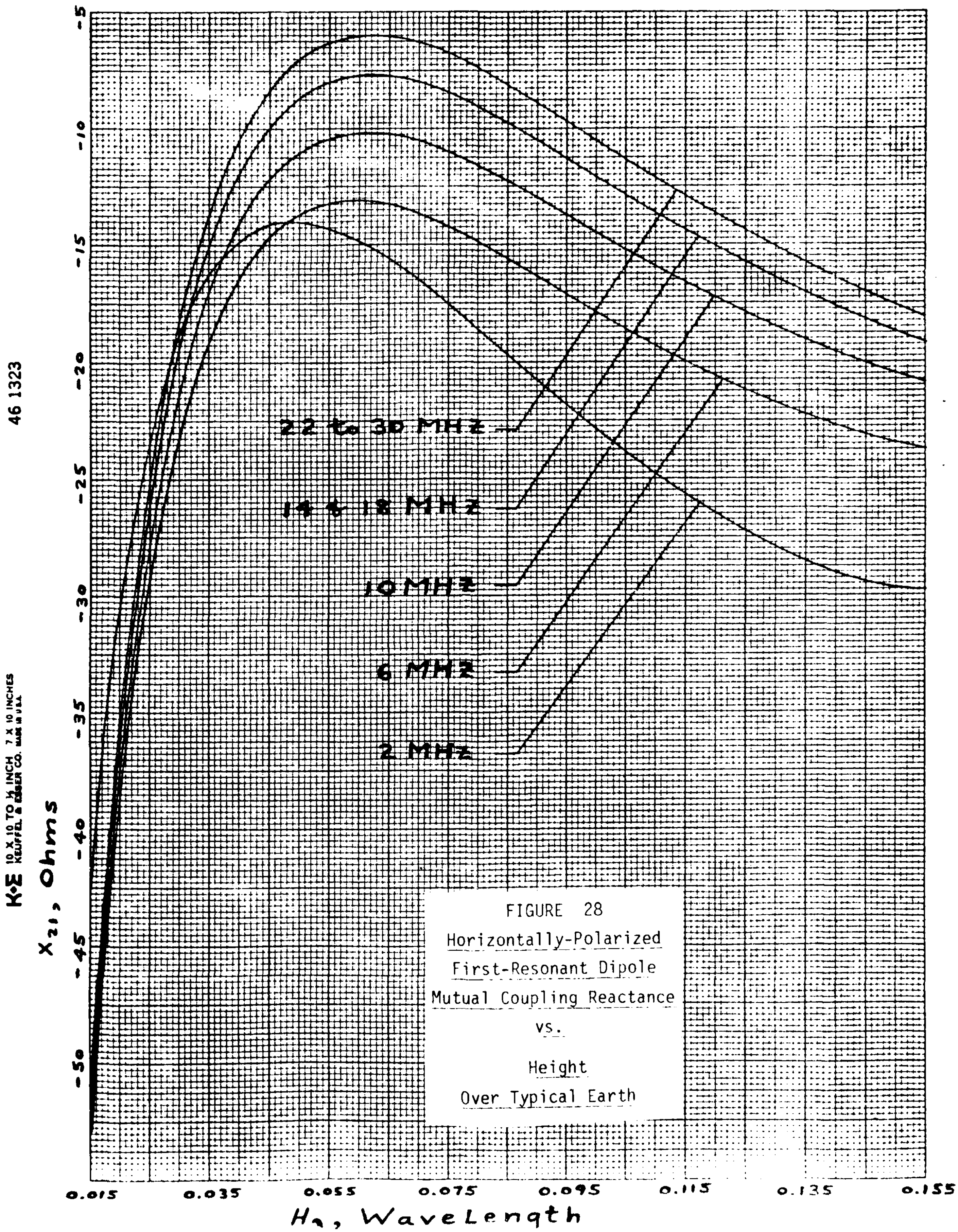


FIGURE 28

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Typical Earth

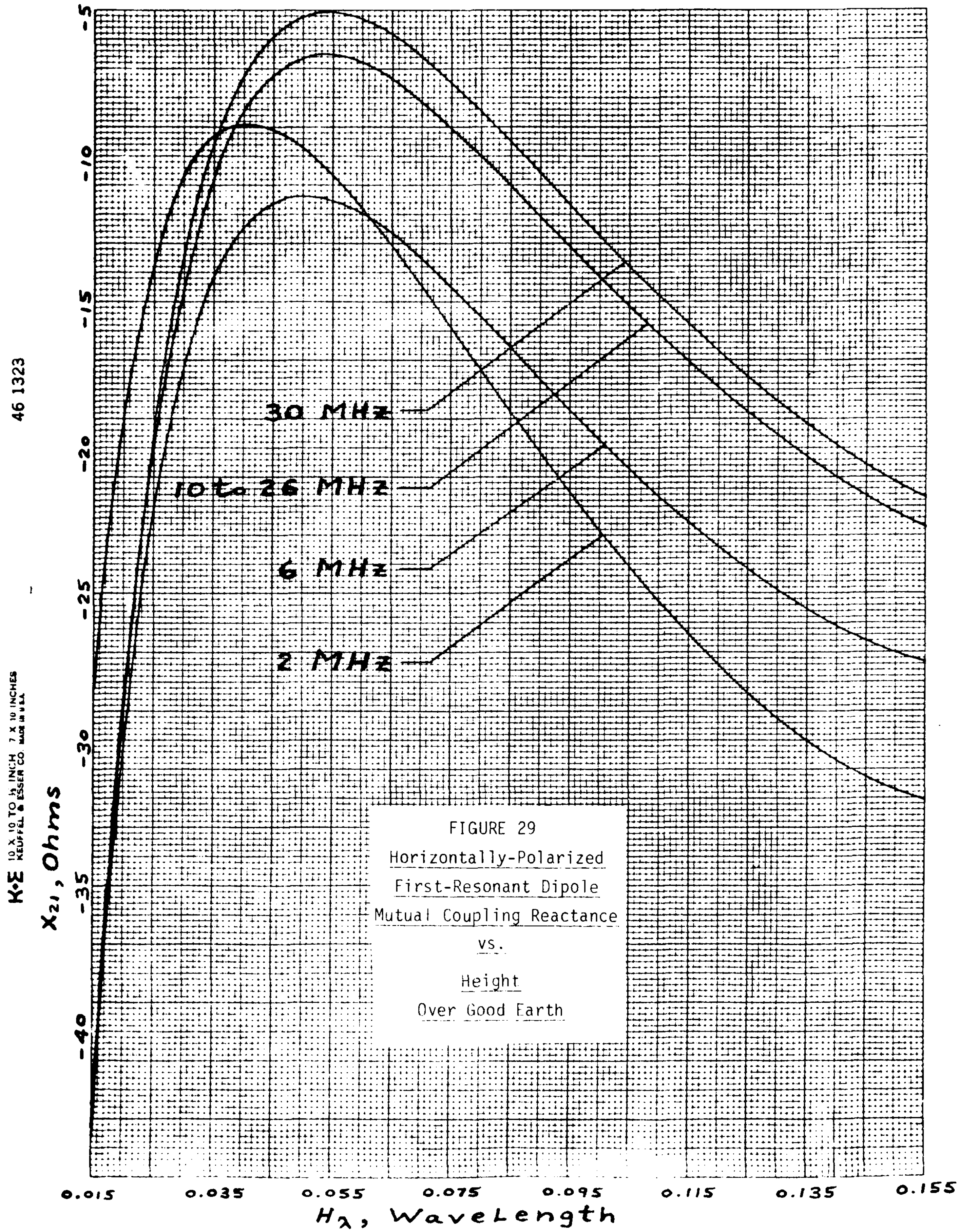


FIGURE 29

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Good Earth

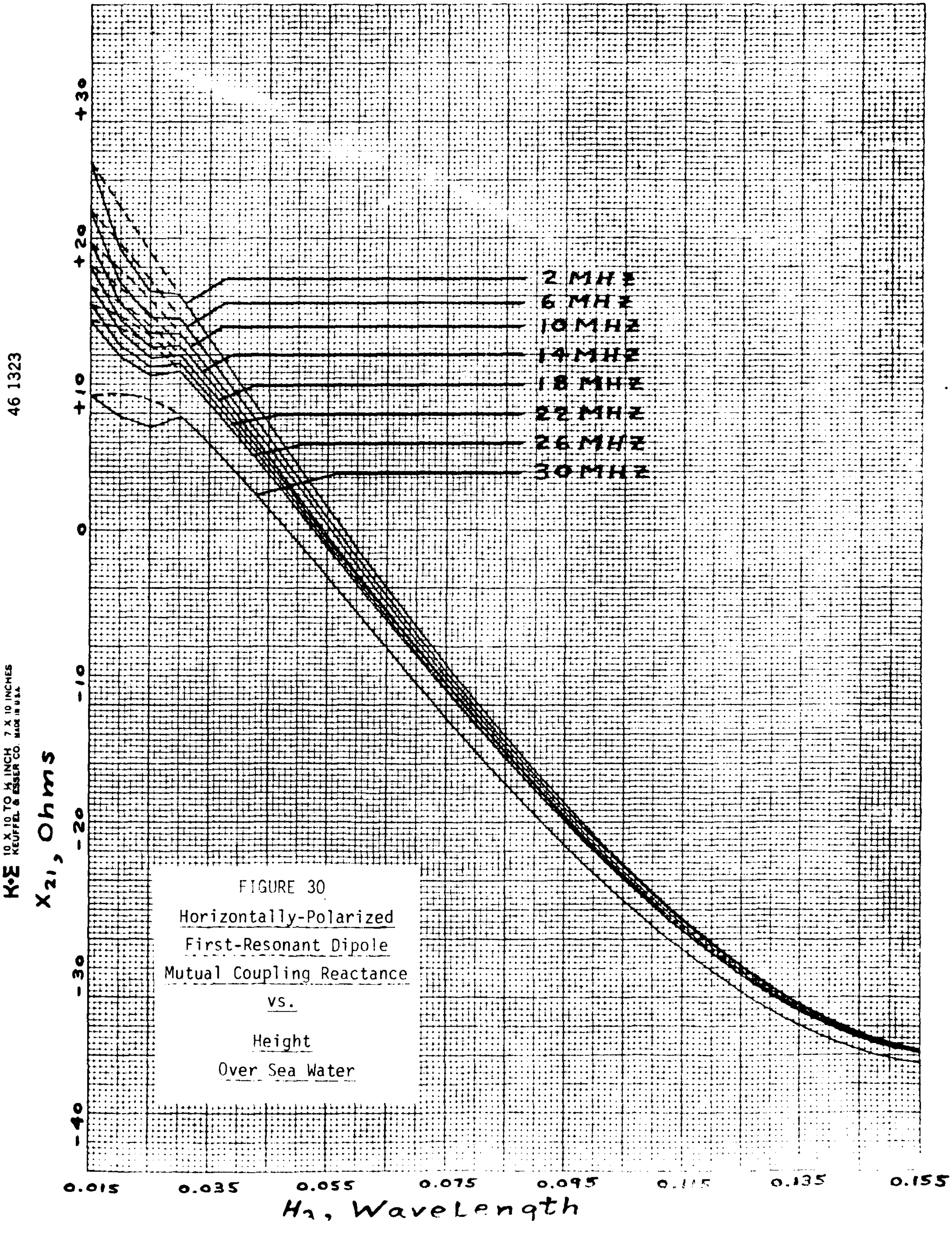


FIGURE 30

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Sea Water

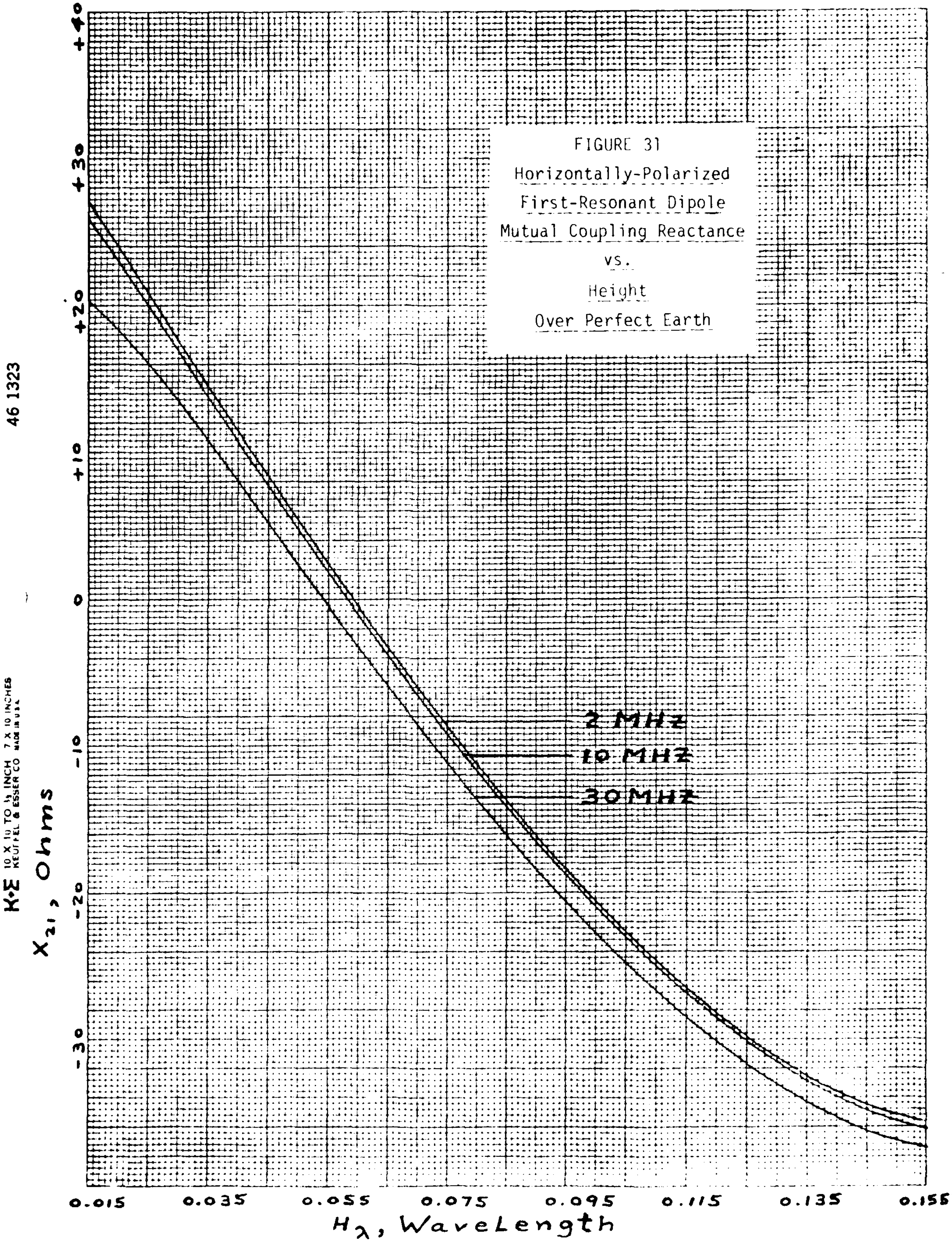


FIGURE 31
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Perfect Earth
2 MHz
10 MHz
30 MHz
+40
+30
+20
+10
0
-10
-20
-30
X_{21}, Ohms
0.015
0.035
0.055
0.075
0.095
0.115
0.135
0.155
H_λ, WaveLength
46 1323
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

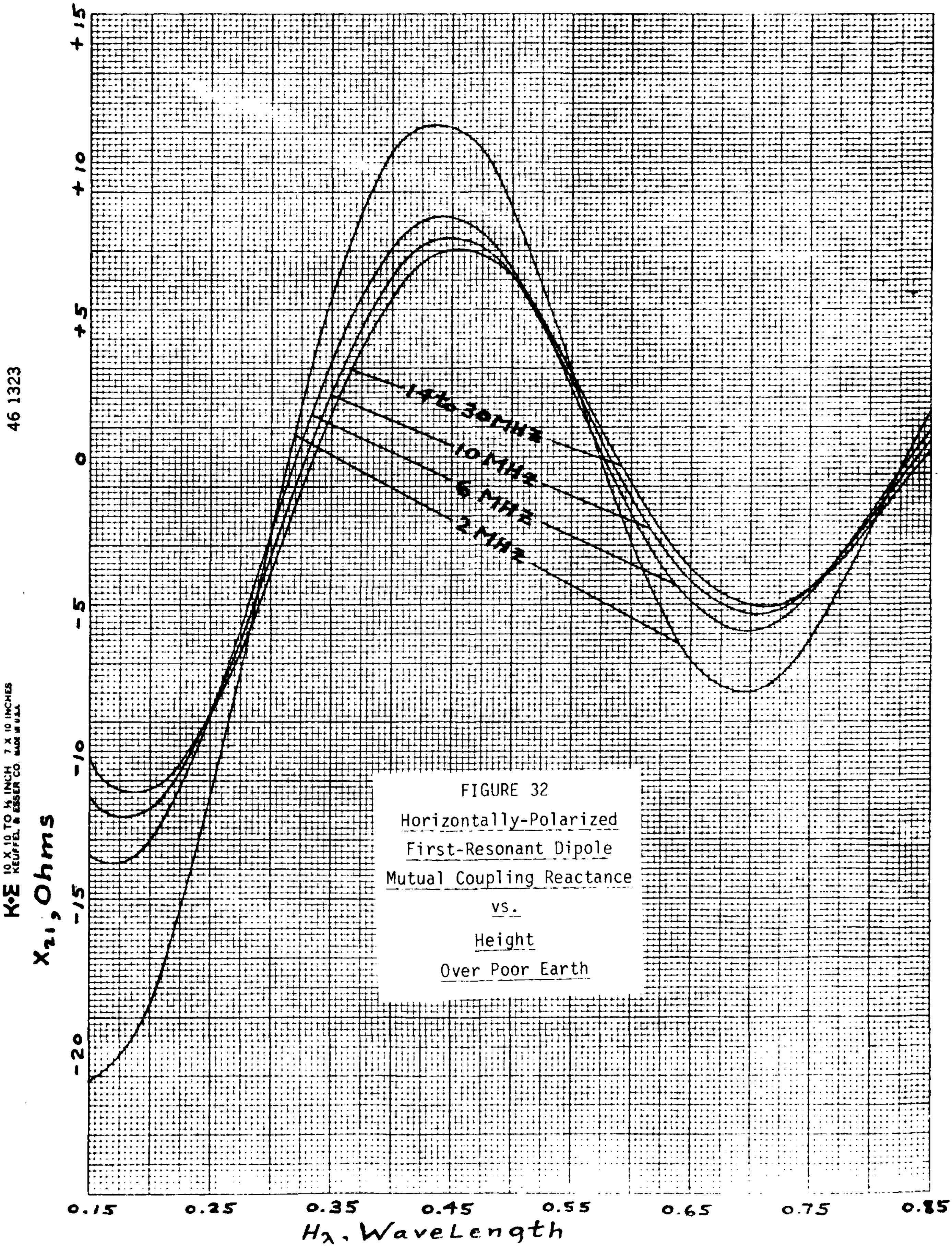


FIGURE 32
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Poor Earth

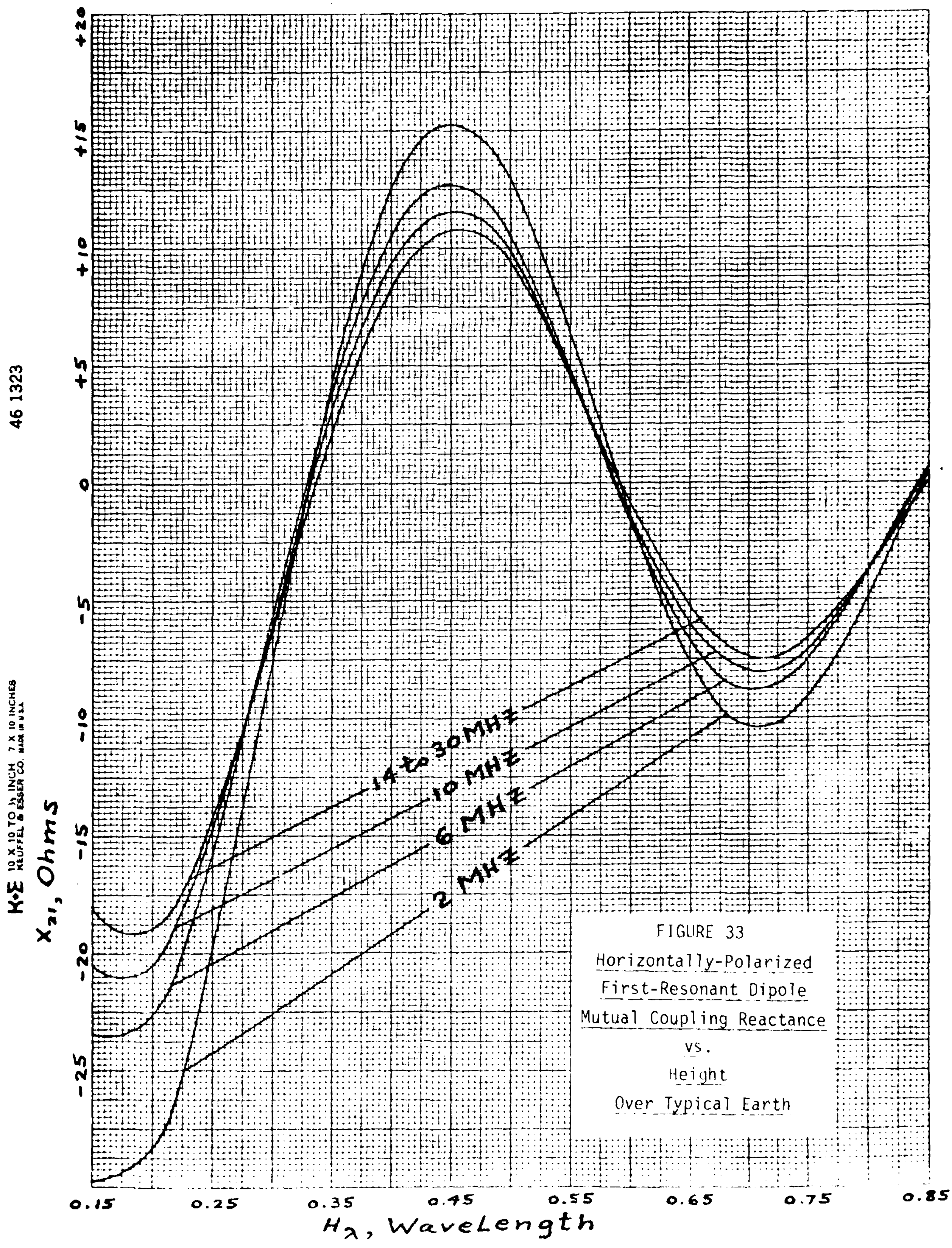


FIGURE 33

Horizontally-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Typical Earth

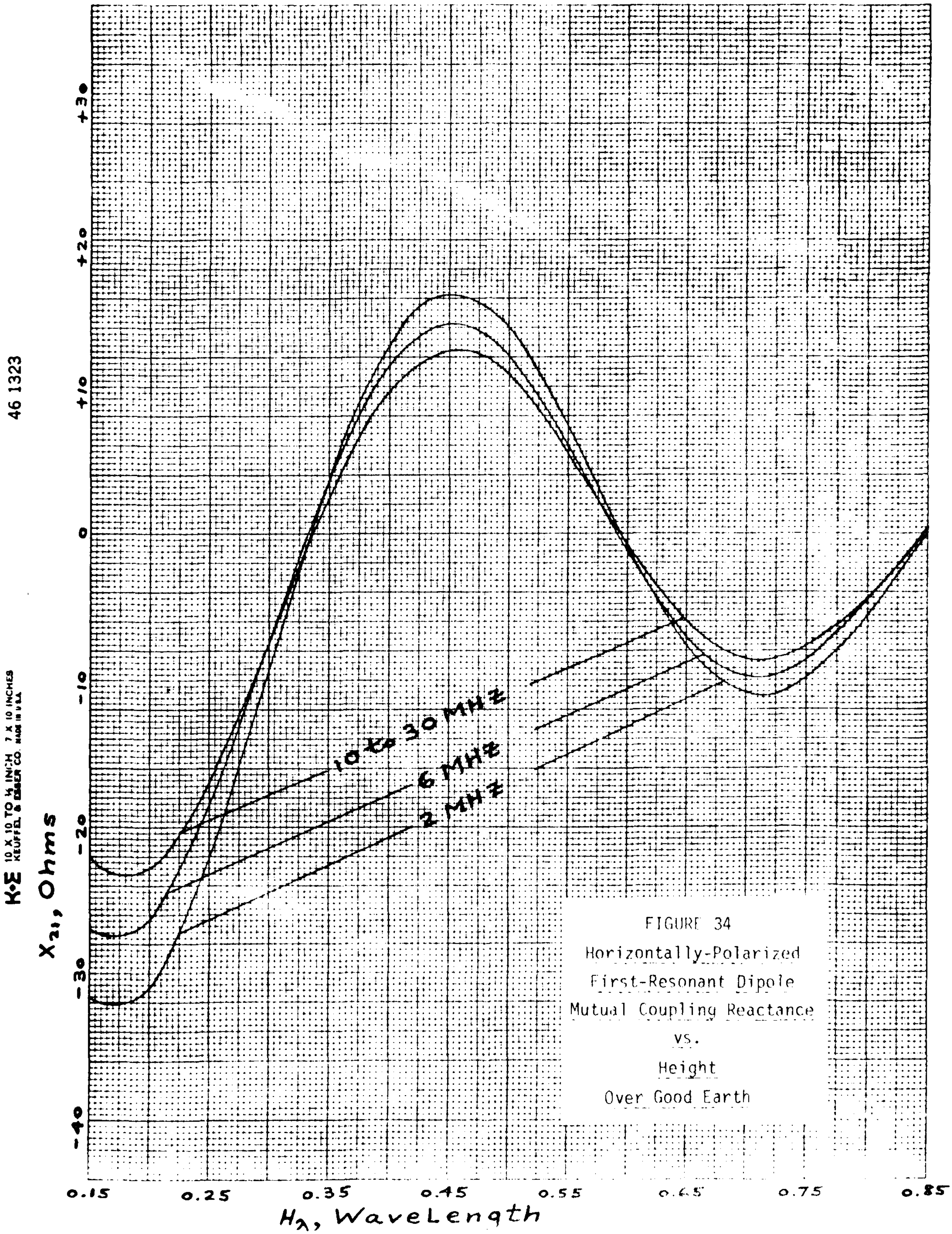


FIGURE 34
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Good Earth

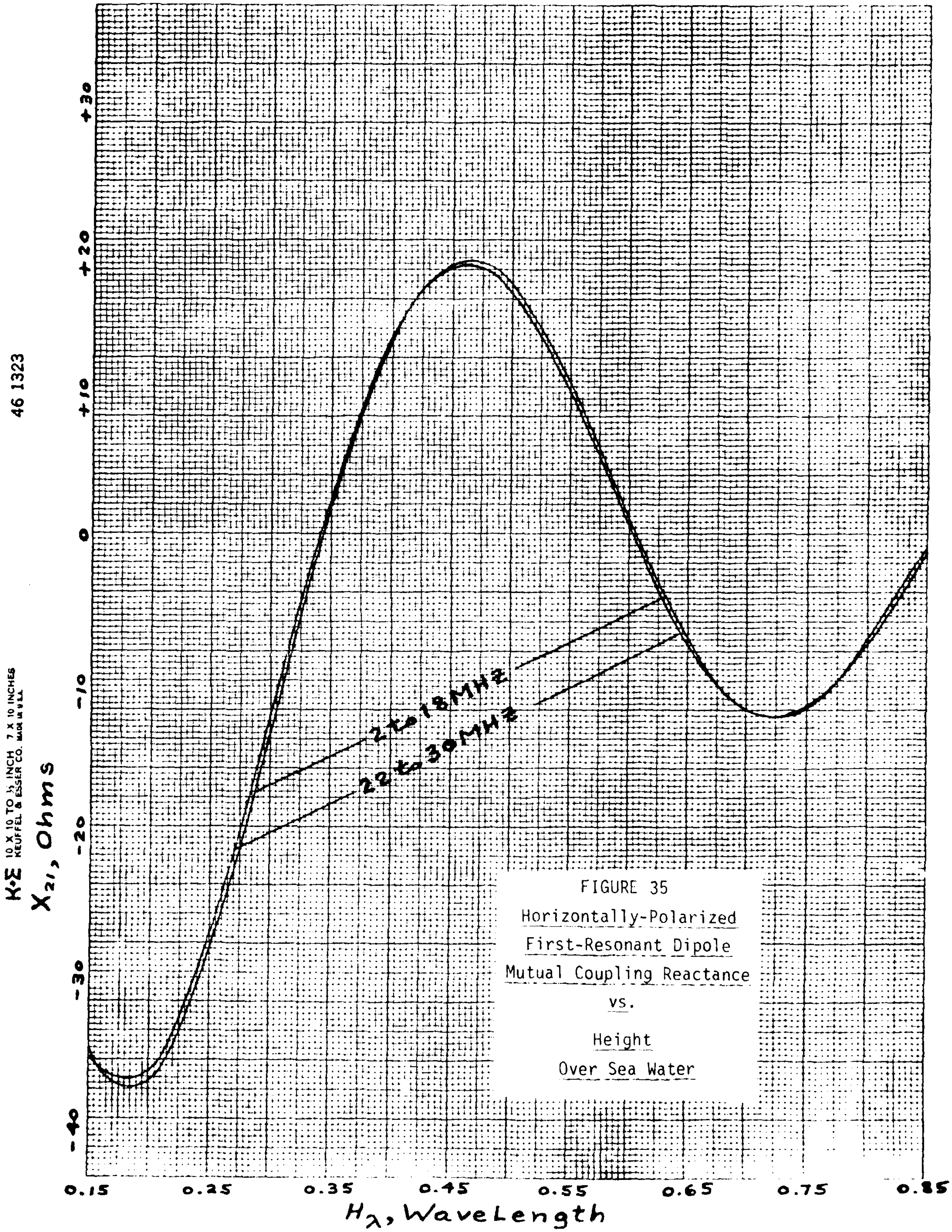


FIGURE 35
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Sea Water

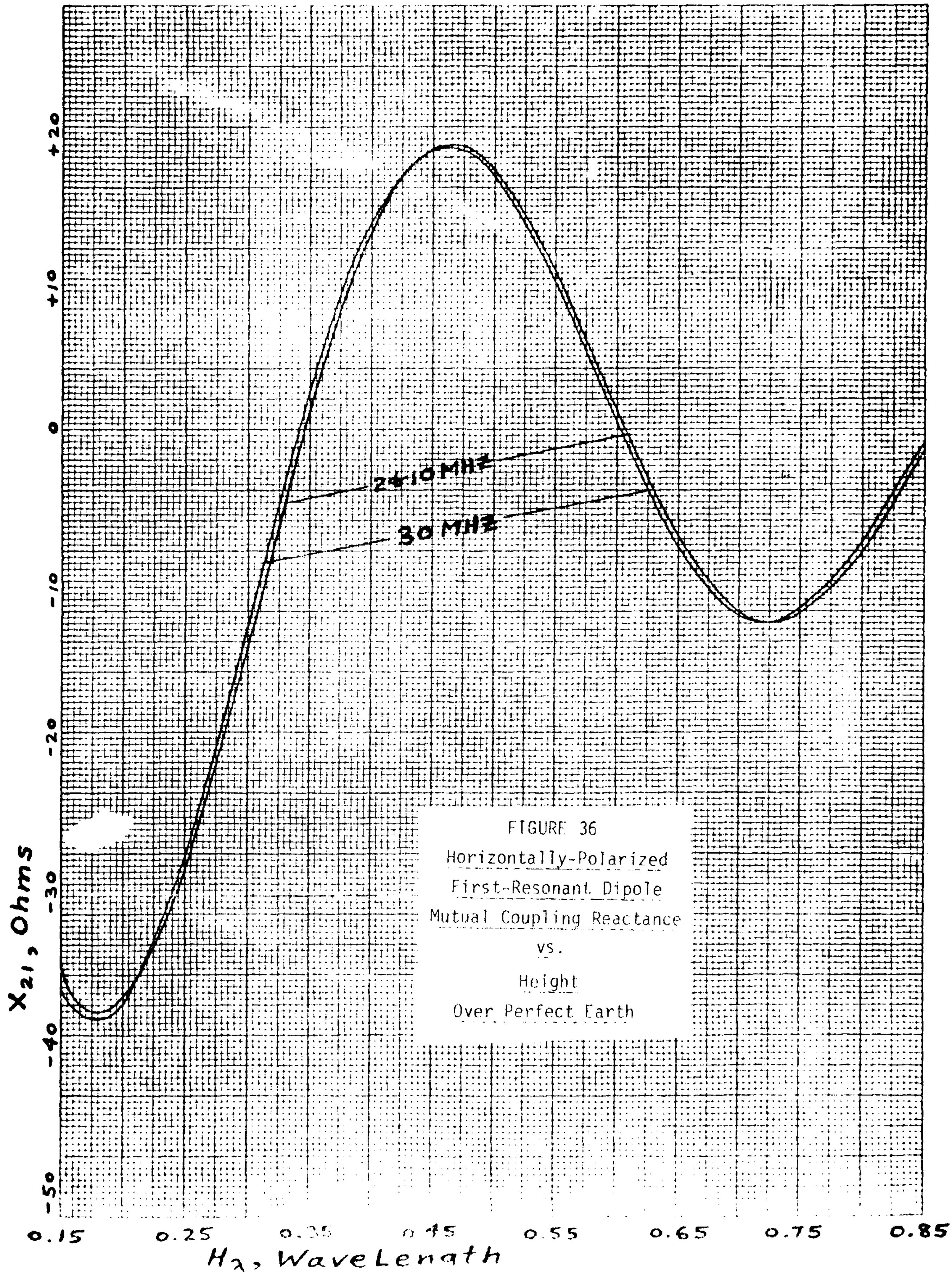


FIGURE 36
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Perfect Earth

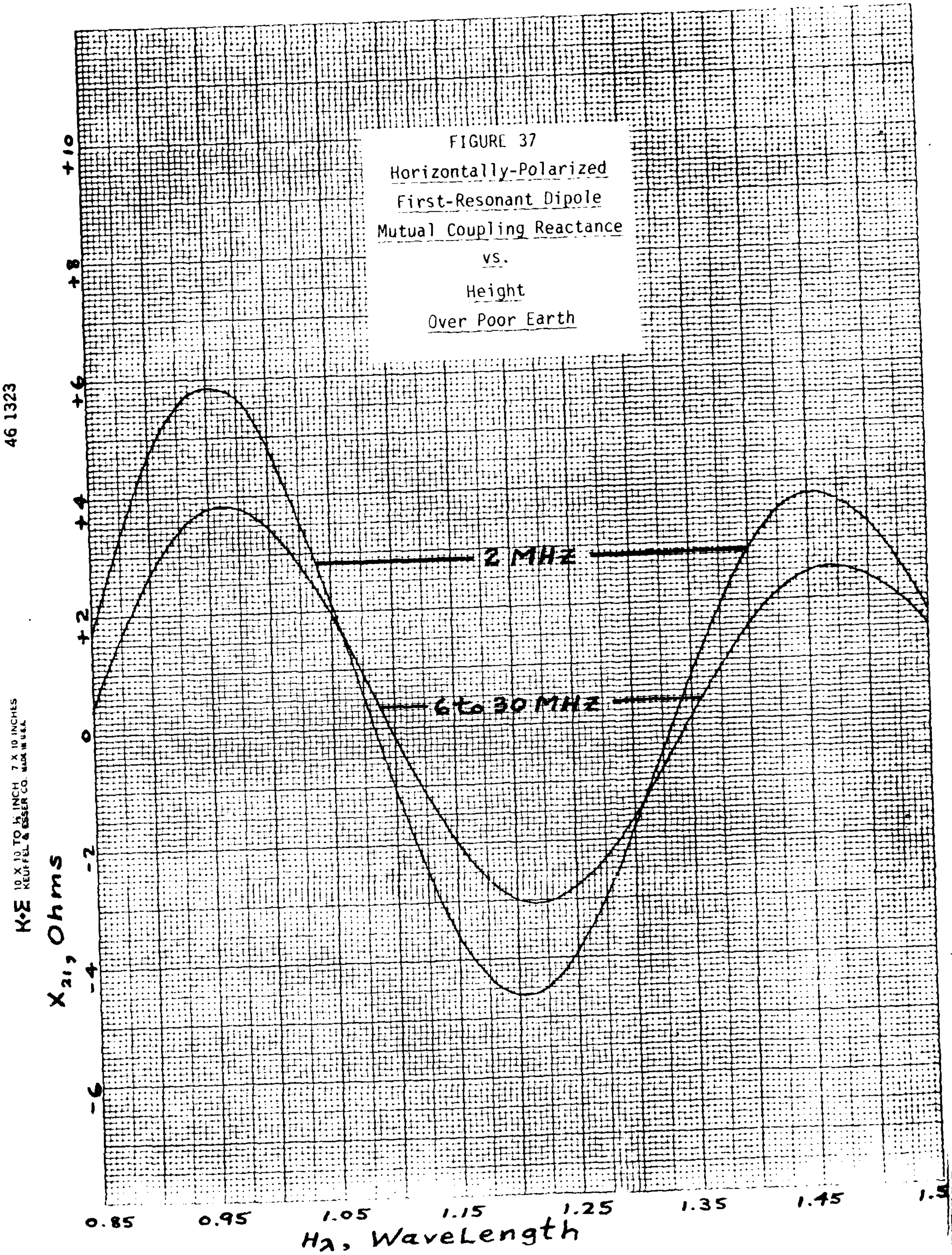
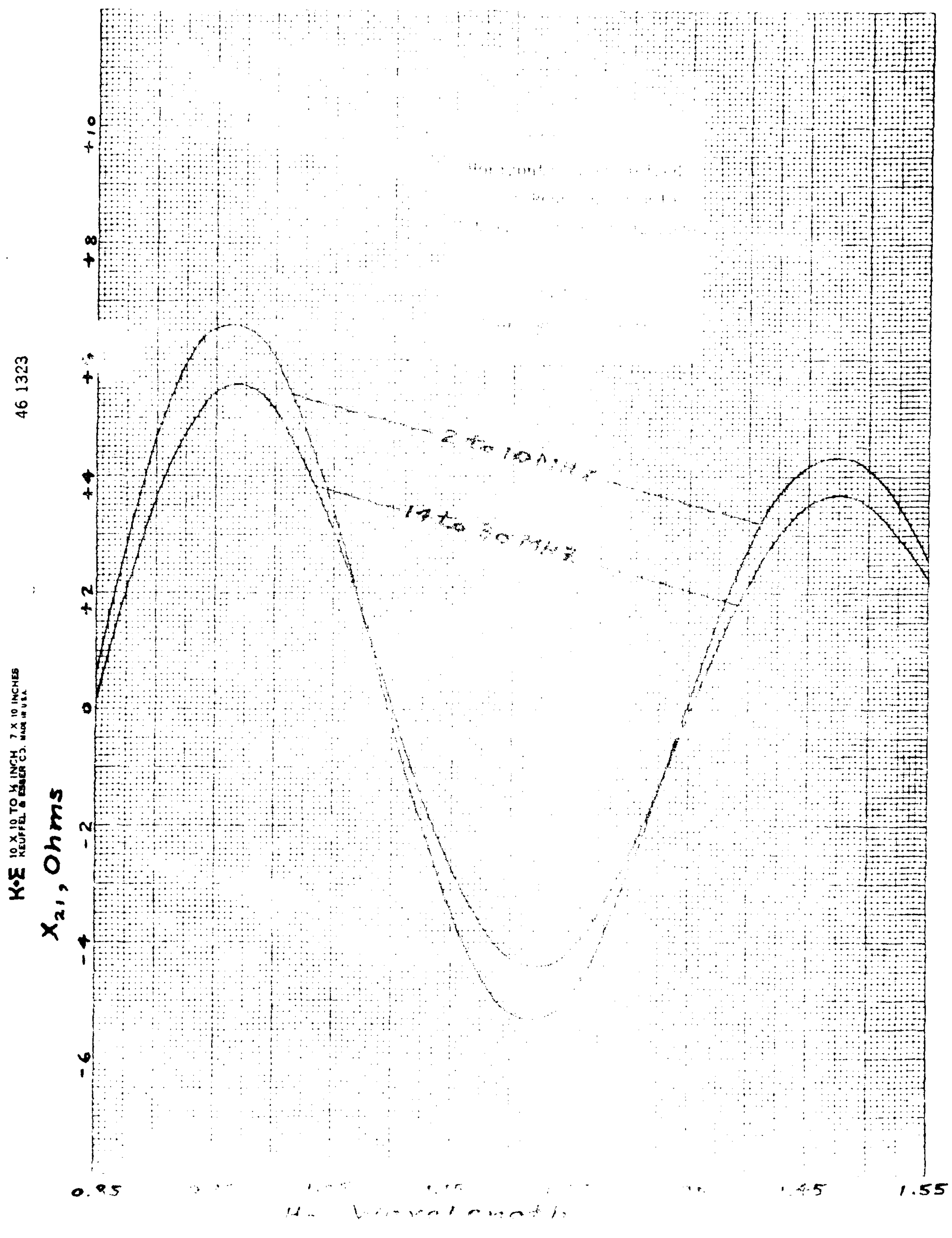


FIGURE 37
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Poor Earth
2 MHZ
6 to 30 MHZ
+10
+8
+6
+4
+2
0
-2
-4
-6
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.5
Hλ, WaveLength
X21, Ohms
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1323


K+E 10 X 10 TO ½ INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1323
X_{21}, Ohms
+10
+8
+4
+2
0
-2
-4
-6
2 to 10 MHz
14 to 30 MHz
0.95
1.45
1.55

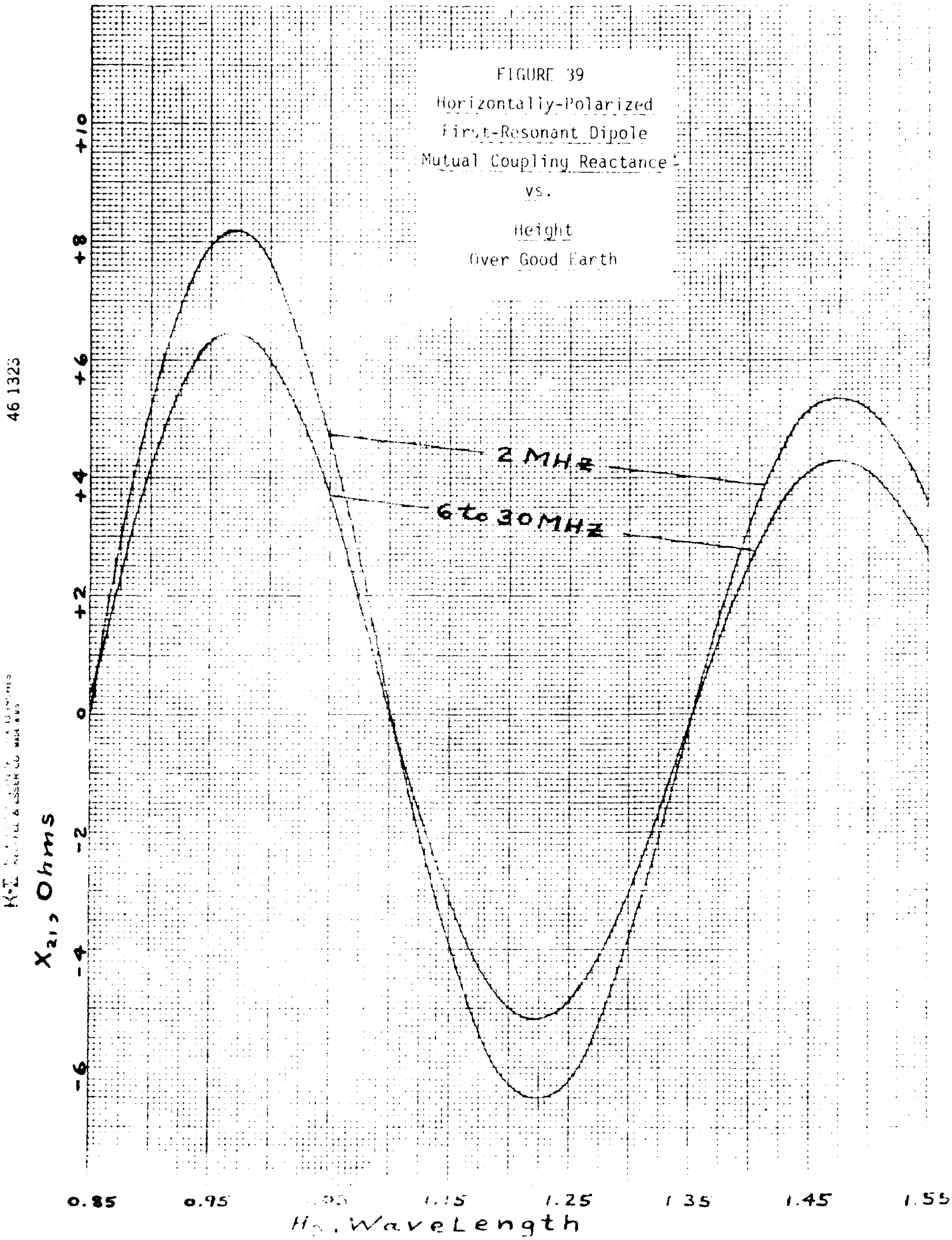
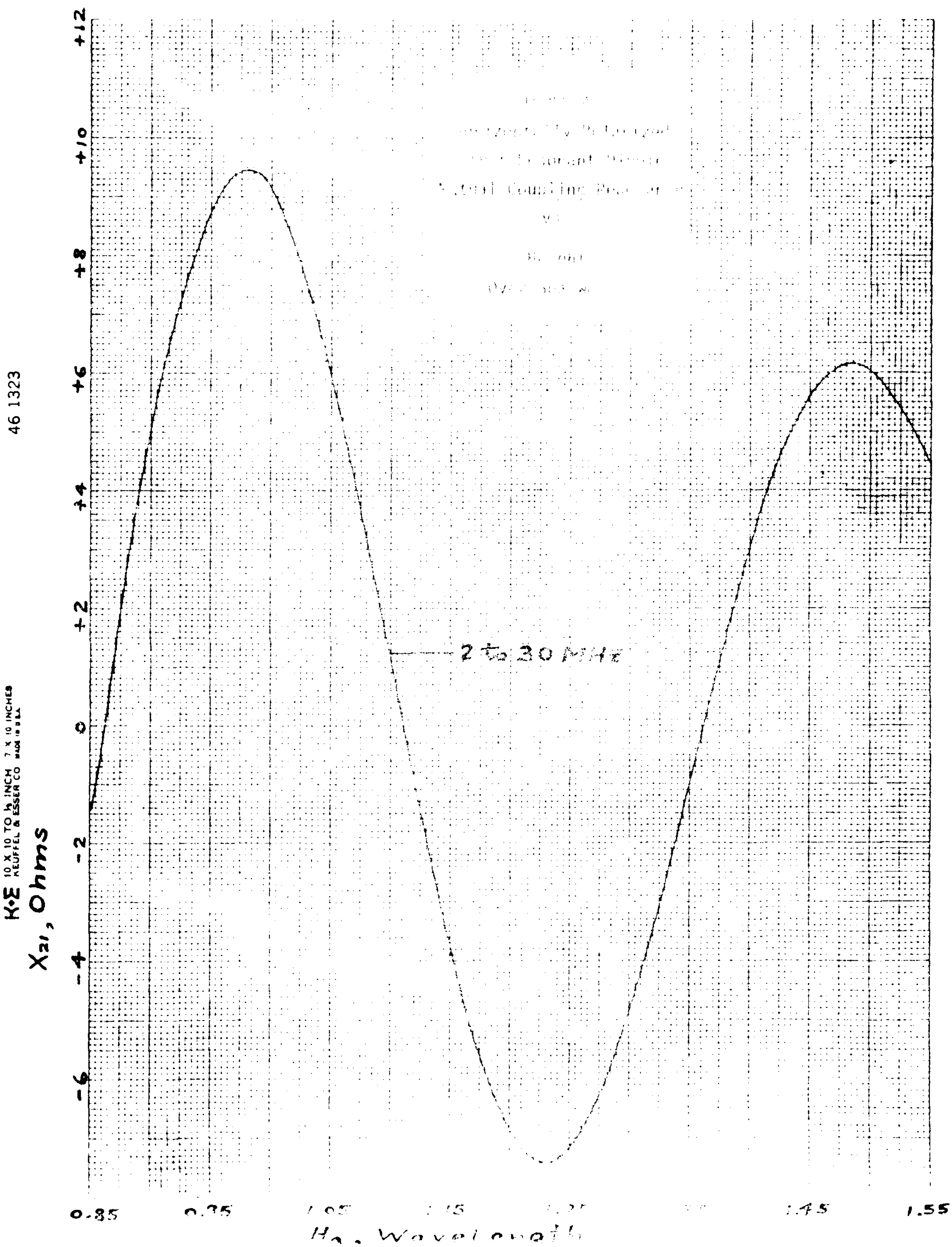
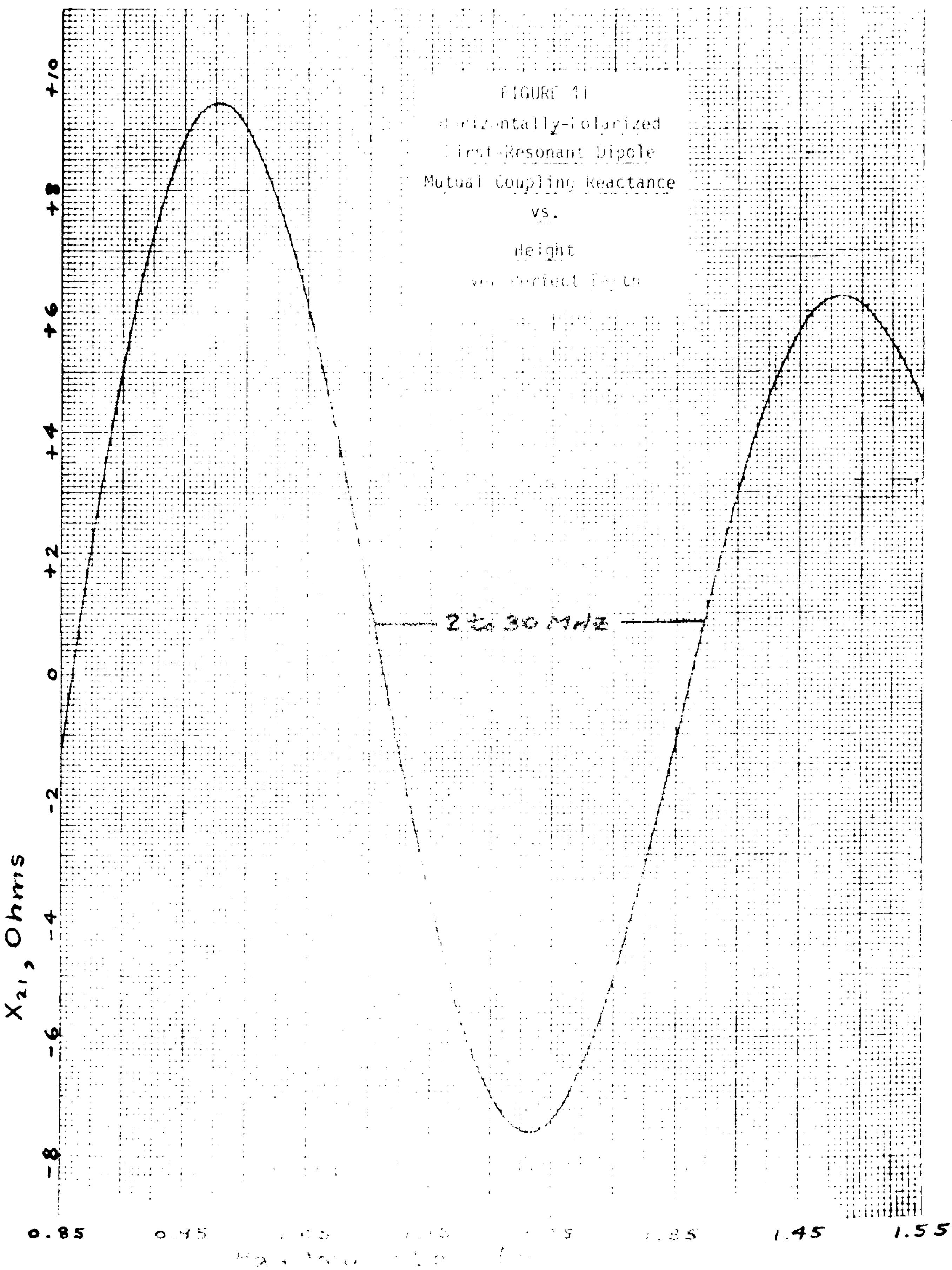


FIGURE 39
Horizontally-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Good Earth



X_{21}, Ohms
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
2 to 30 MHz
0.85
0.95
1.05
1.15
1.25
1.45
1.55
46 1323
K·E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO.



Mutual Coupling Reactance
vs.
Height
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
X21, Ohms
2 to 30 MHz
0.85
1.45
1.55

The [illegible] show that mutual reactance is highly capacitive when this antenna is near [illegible] earth and, from equation 4, the antenna impedance becomes highly [illegible]. [illegible], at some of the low heights, the mutual appears to be quite [illegible] to both frequency and earth electrical properties. As an example, [illegible] that a [illegible] horizontal dipole is [illegible] at a height of [illegible] over poor earth. What happens to the input impedance when [illegible] dipole is erected at the same height over good earth? Using Figures [illegible] and 27 in the first [illegible],

$$Z_{in} = Z_{11} + [illegible] \ldots 7 + j\,14.0)$$

$$[illegible] + 14.0) \quad \text{ohms}$$

Using [illegible] in the second case,

$$Z_{in} = [illegible] \ldots (24.6 \ldots 16.5)$$

$$[illegible] = 3[illegible] \quad \text{ohms}$$

In the first case, it was necessary to shorten the dipole arms to achieve resonance over poor earth [illegible] the mutual reactance [illegible] the dipole impedance appear inductive. [illegible] reduced the dipole free-space input resistance [illegible] than 8.27 ohms. In the second case, the dipole input resistance is reduced further, and the dipole input reactance is again inductive so that the dipole arms must be shortened further to achieve resonance. Thus, in this example, the first resonant dipole is longer over [illegible] earth than it is over good earth, and this has been observed in the [illegible].

The results shown on Figure 26 are what one would expect. The mutual reactance, X_{21}, of the free-space [illegible] resonant dipole approaches zero ohms when the height, H, approaches the dipole radius, and the mutual reactance solutions on Figure 26 are a function of dipole first-resonant lengths of 0.[illegible]88386λ at 2.[illegible] MHz, 0.[illegible] at [illegible] MHz, and 0.473683λ at 30.0 MHz discussed previously.

The results plotted on Figure 30 show that NEC solutions are not correct when the dipole height is $0.015 < H_\lambda < 0.03$ wavelength over sea water. This is consistent with the results obtained in Section II, and indicates that NEC - with its existing equations - is not valid over sea water at HF when H_λ is in this region

IV. VERTICALLY-POLARIZED MUTUAL RESISTANCE.

The mutual resistance, [illegible], results are plotted on Figures 42-46 for $0.25 \leq H_\lambda \leq 0.95$ wavelengths. That is, there are 5 graphs over this range of H_λ, one for each height listed, and the frequency or frequency range is plotted on each graph.

These figures show that mutual resistance is highly positive when this antenna is near ground. At the [illegible], this mutual resistance is not highly sensitive to changes in frequency or earth electrical properties at HF.

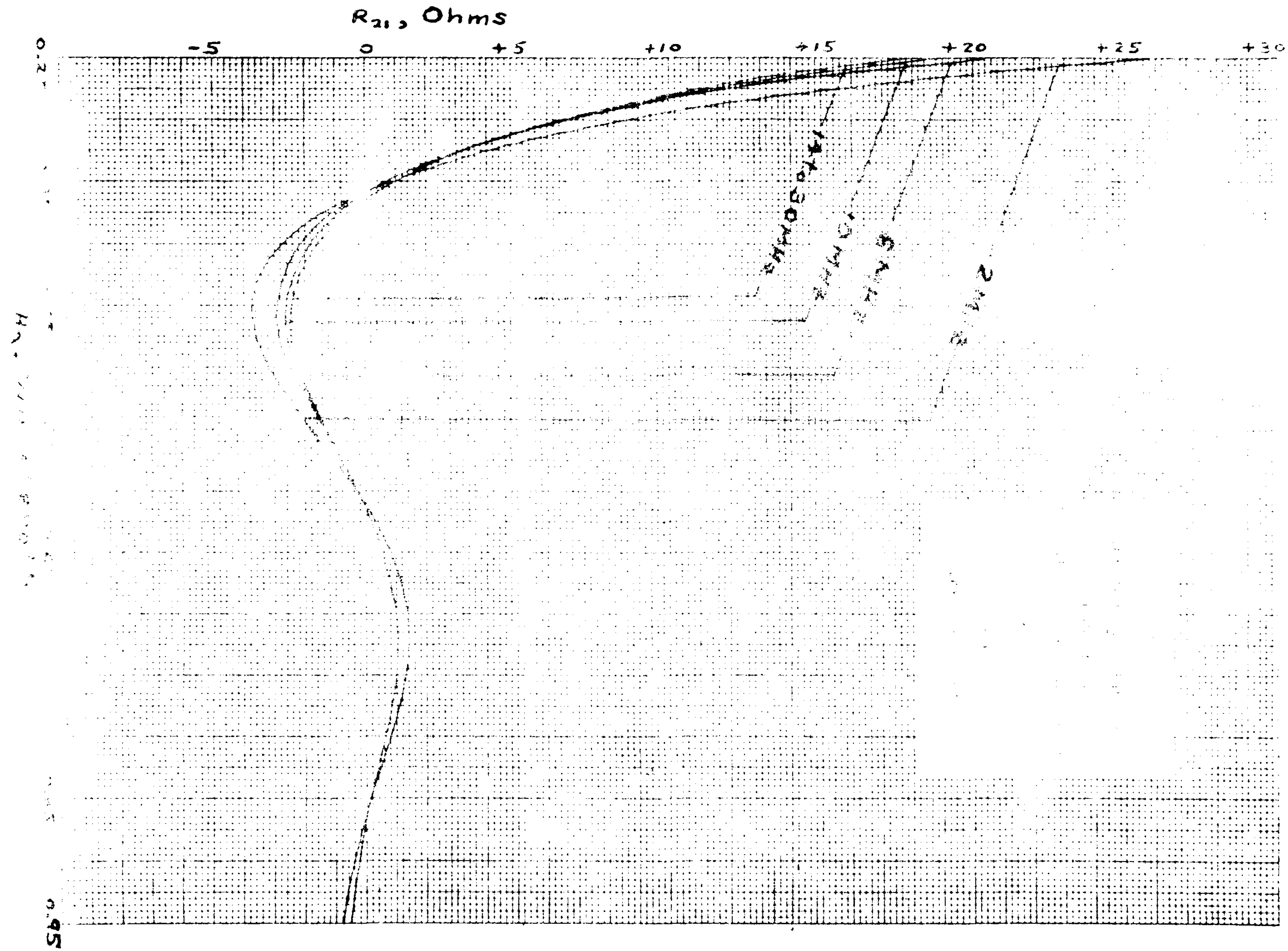
These figures appear to be highly accurate, and vertically-polarized mutual resistance is not very significant at HF when H_λ [illegible] 0.6 wavelength over ground with the [illegible] electrical properties.

V. VERTICALLY-POLARIZED MUTUAL REACTANCE.

The mutual reactance, [illegible], results are plotted on Figures 47-51 for $0.25 \leq H_\lambda \leq 0.95$ wavelengths. That is, there are 5 graphs over this range of H_λ, one for each height listed, and the frequency or frequency range is plotted on each graph.

These figures show that mutual reactance is always positive when this antenna is near ground. This mutual reactance is not highly sensitive to changes in frequency or earth electrical properties at HF. The apparent sensitivity to frequency is really a sensitivity to dipole length at first resonance (in terms of L/D).

K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1323



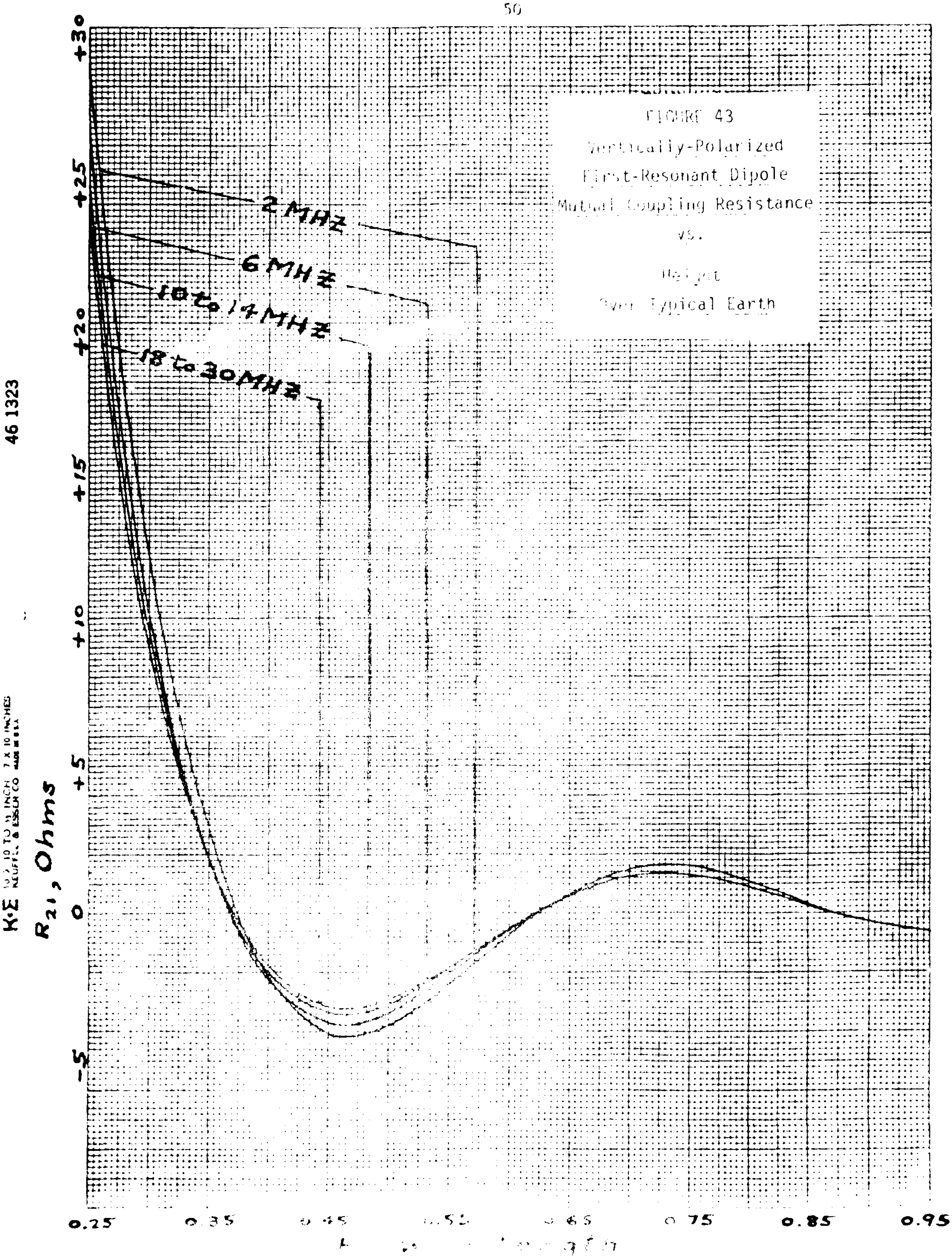


FIGURE 43
Vertically-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Typical Earth

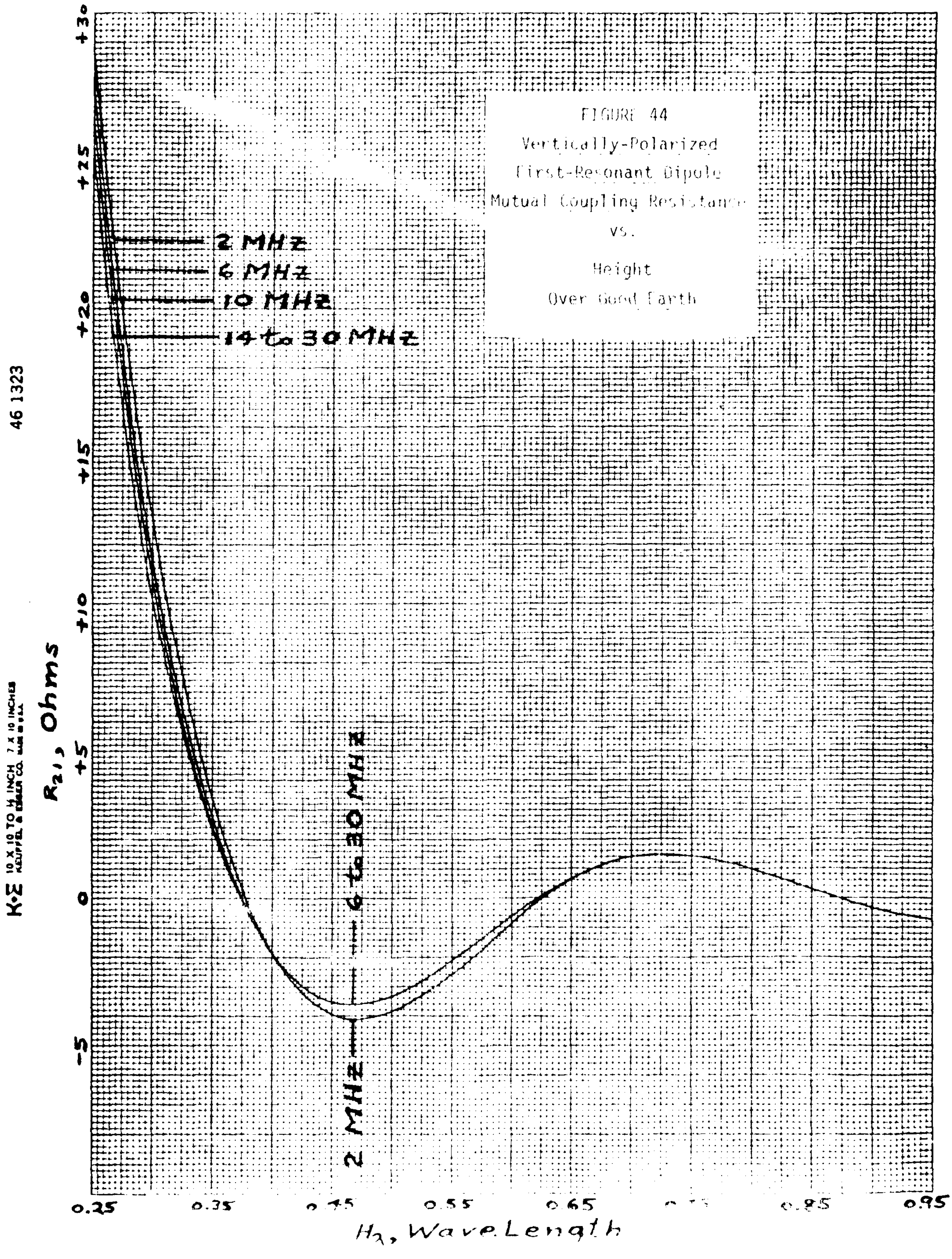


FIGURE 44
Vertically-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Good Earth
2 MHz
6 MHz
10 MHz
14 to 30 MHz
6 to 30 MHz
2 MHz
+30
+25
+20
+15
+10
+5
0
-5
R_{21}, Ohms
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
H_λ, Wave Length
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.
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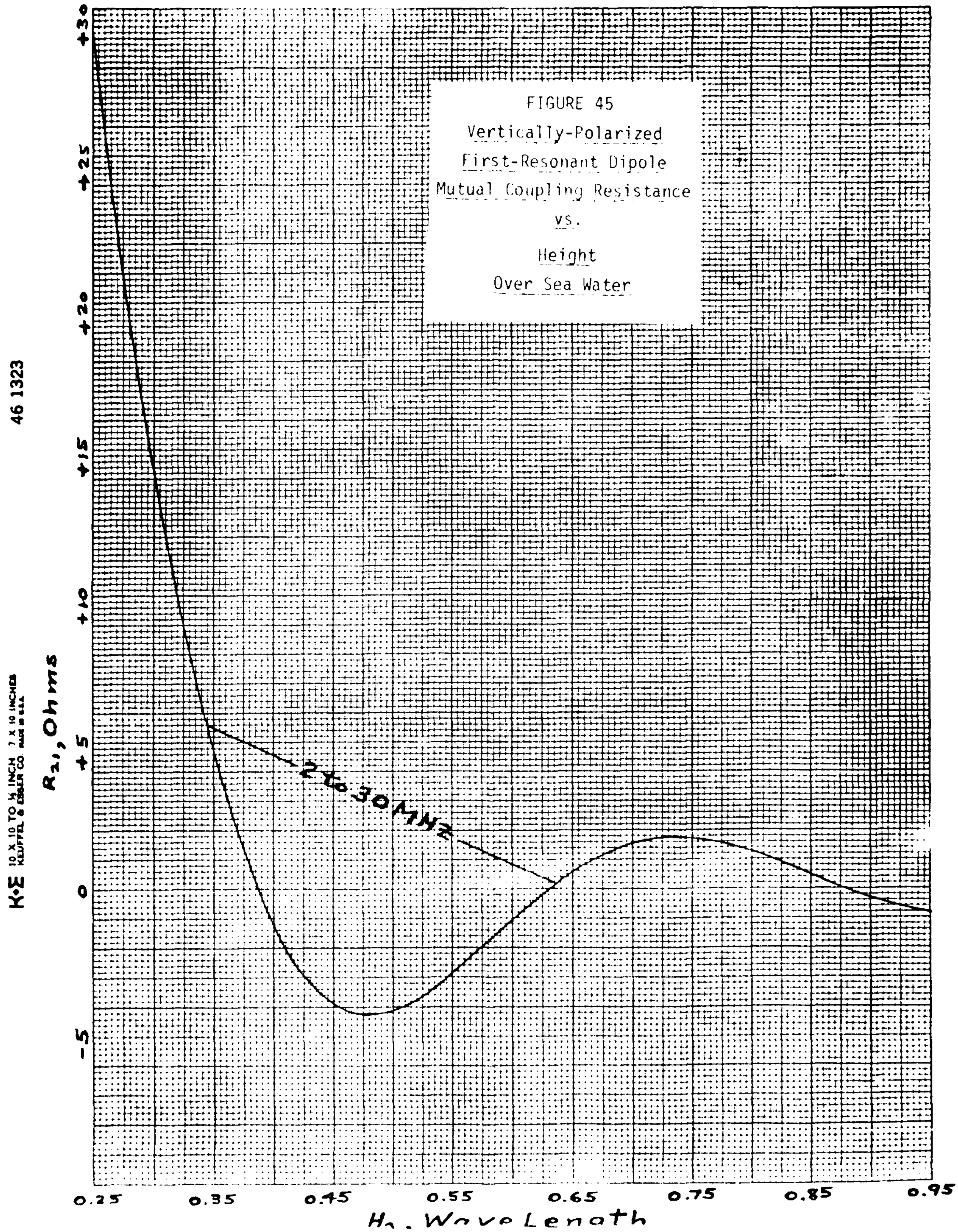

FIGURE 45
Vertically-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Sea Water

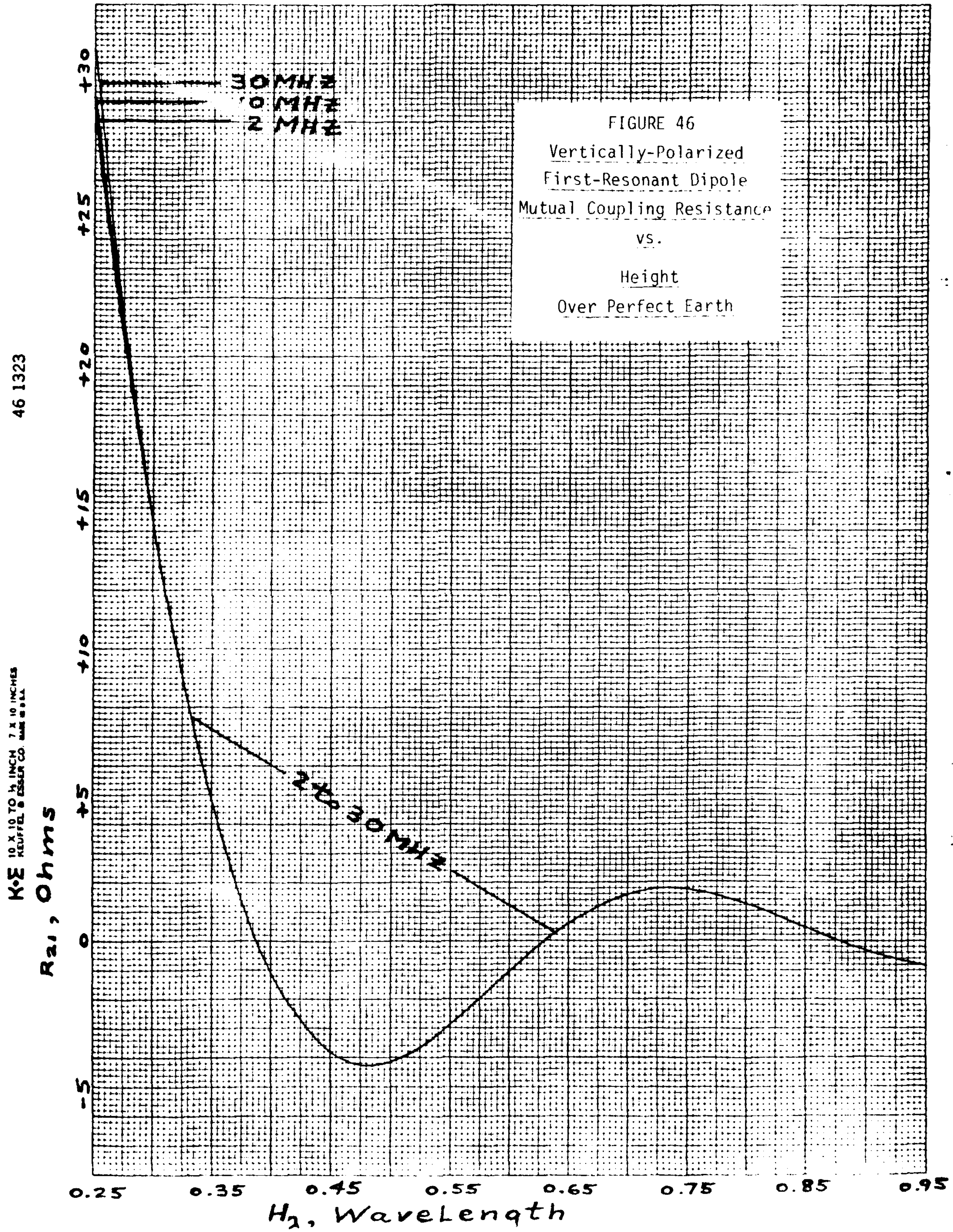
FIGURE 46
Vertically-Polarized
First-Resonant Dipole
Mutual Coupling Resistance
vs.
Height
Over Perfect Earth
30 MHZ
10 MHZ
2 MHZ
2 to 30 MHZ
+30
+25
+20
+15
+10
+5
0
-5
R_{21}, Ohms
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
H_2, Wavelength
46 1323
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

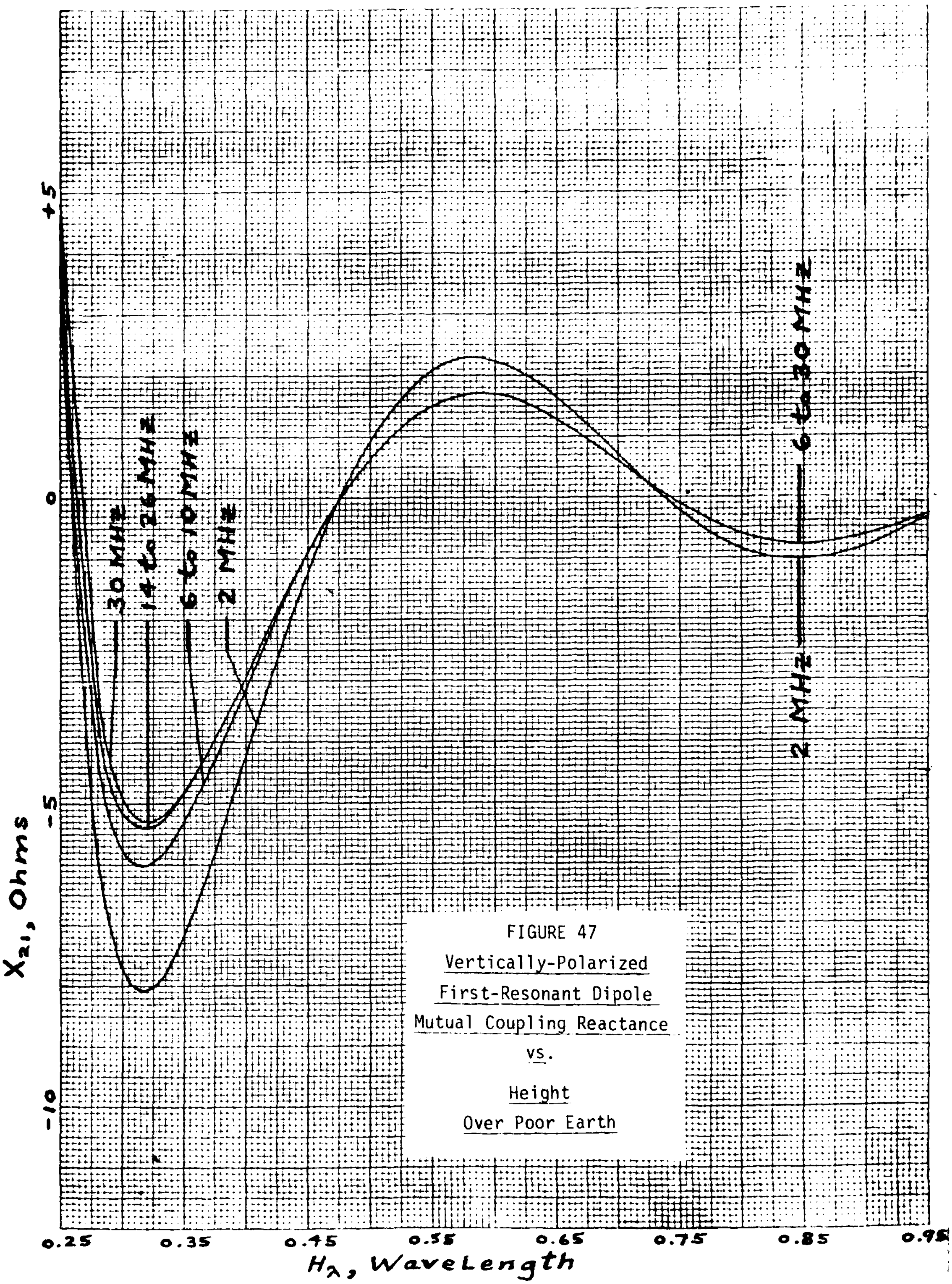

FIGURE 47

Vertically-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Poor Earth

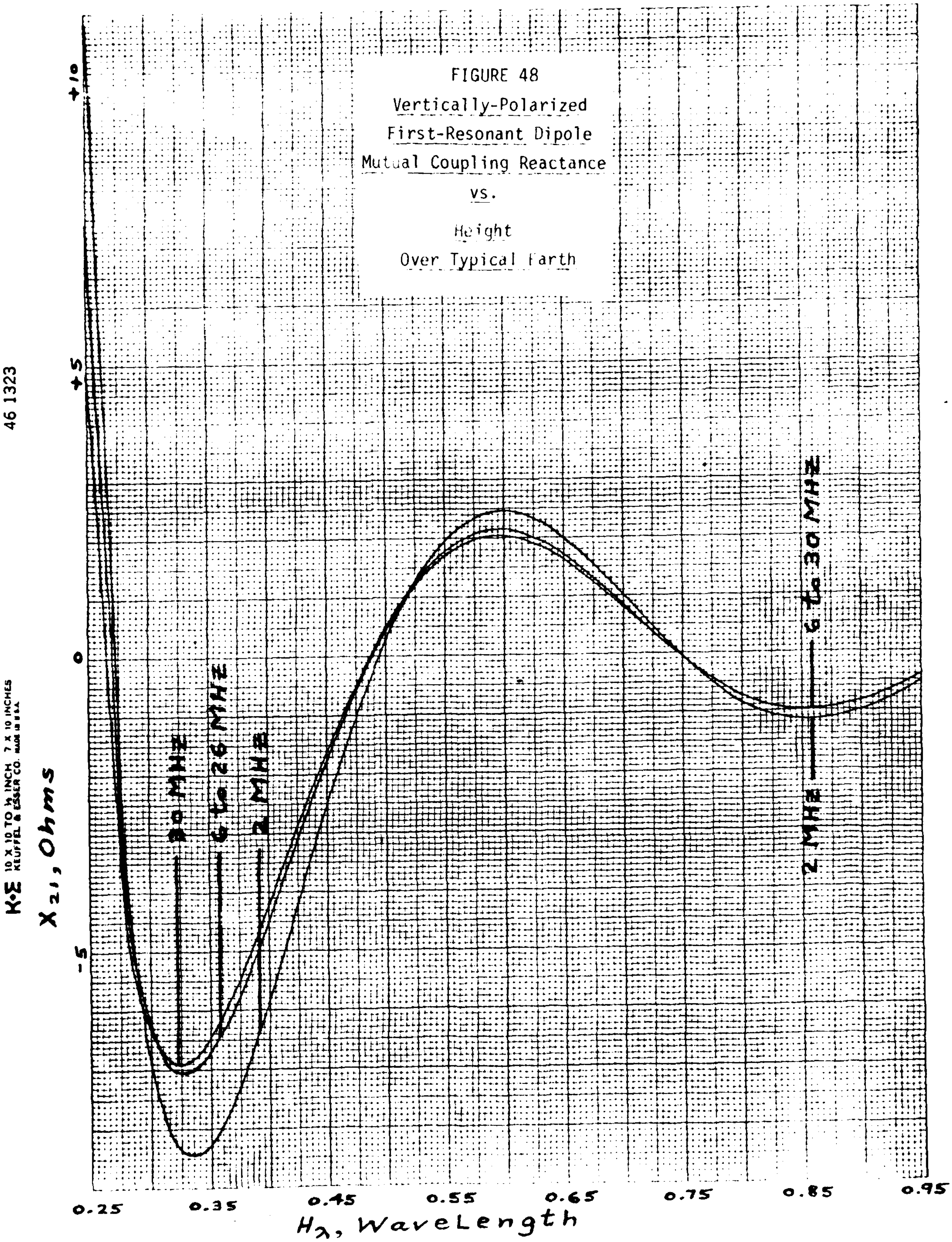

FIGURE 48
Vertically-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Typical Earth

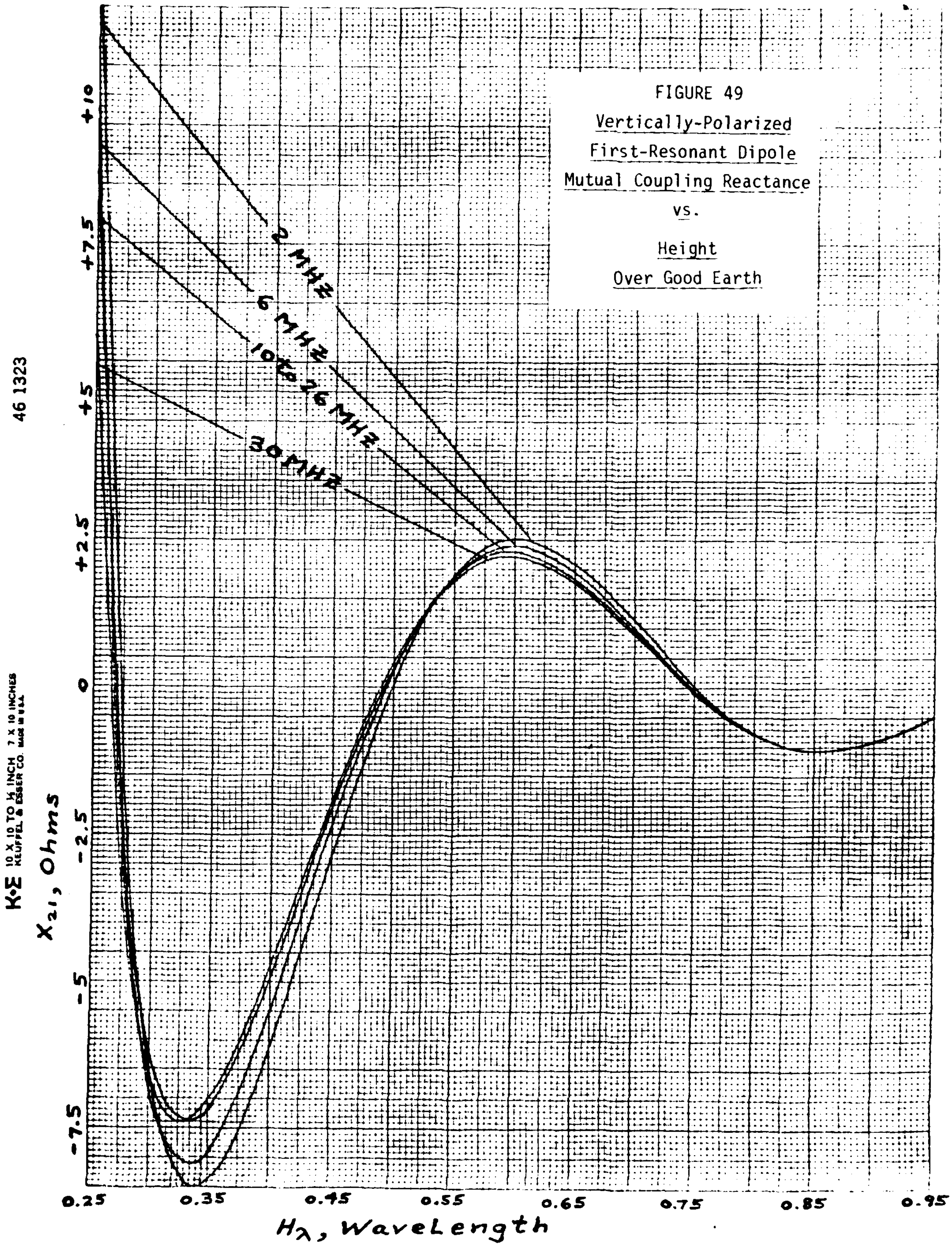
FIGURE 49
Vertically-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Good Earth
2 MHz
6 MHz
10 to 26 MHz
30 MHz
+10
+7.5
+5
+2.5
0
-2.5
-5
-7.5
X21, Ohms
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
Hλ, Wavelength
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1323

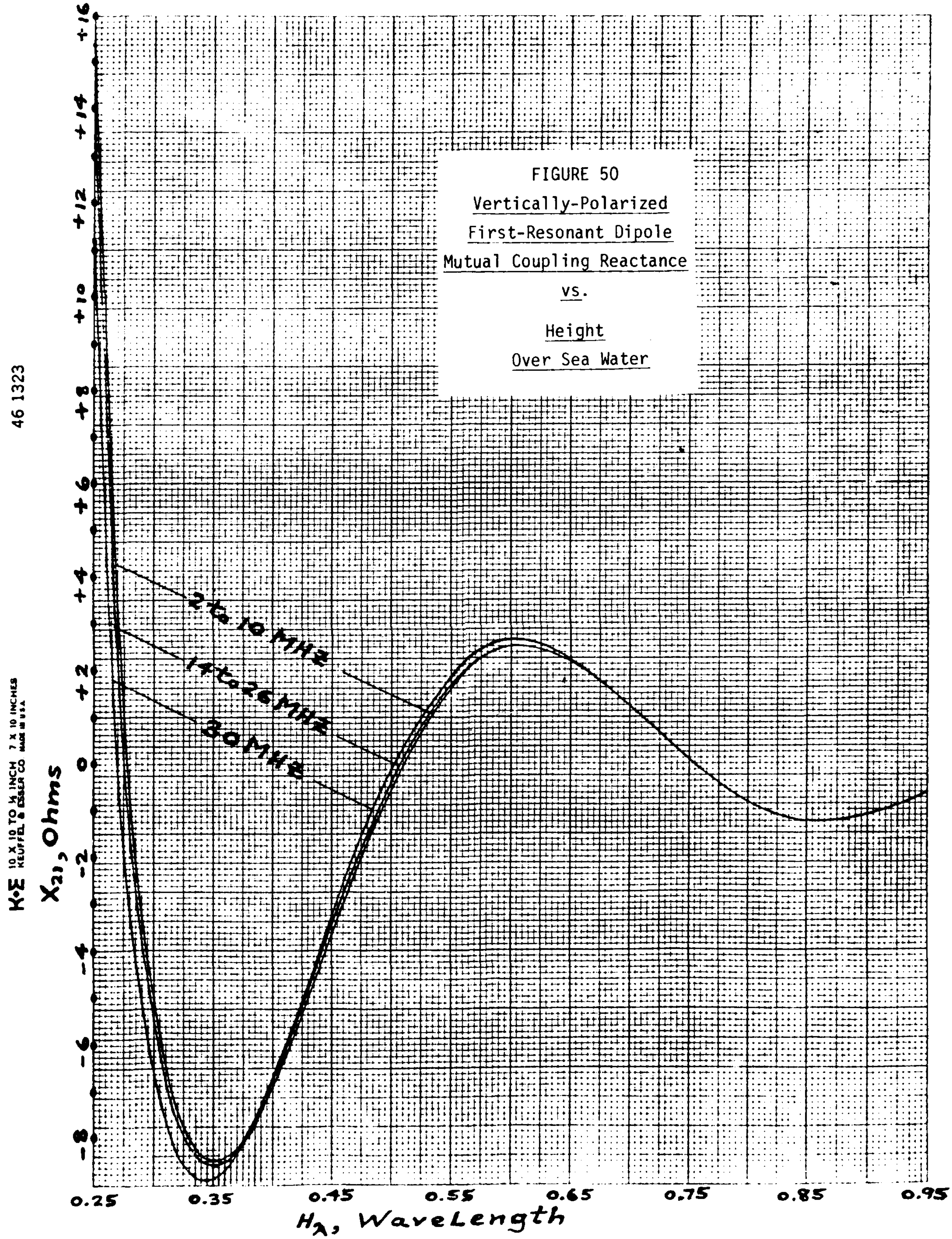
FIGURE 50
Vertically-Polarized
First-Resonant Dipole
Mutual Coupling Reactance
vs.
Height
Over Sea Water
2 to 10 MHz
14 to 26 MHz
30 MHz
+16
+14
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
X_{21}, Ohms
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
H_λ, WaveLength
46 1323
K•E 10 X 10 TO ½ INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

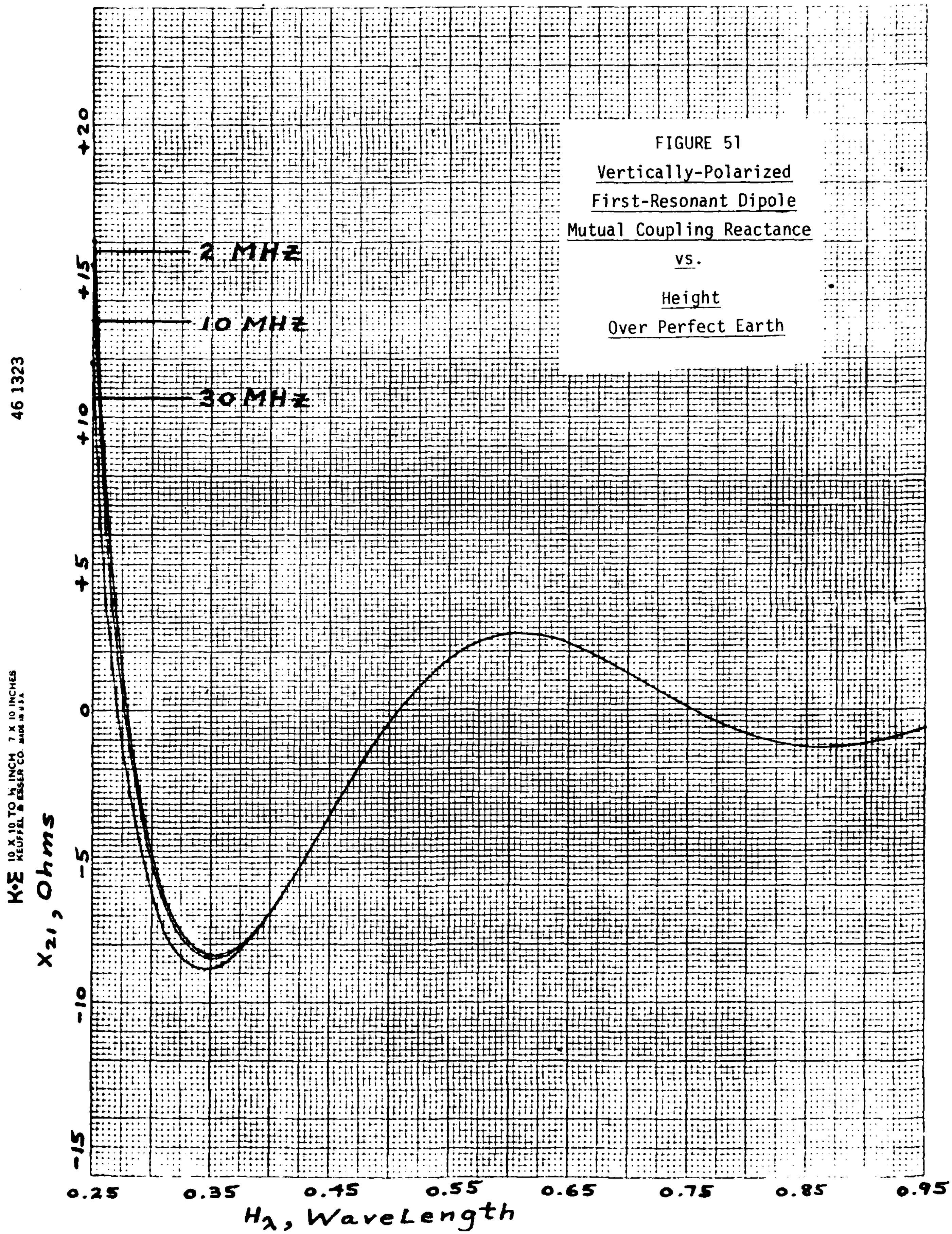

FIGURE 51

Vertically-Polarized

First-Resonant Dipole

Mutual Coupling Reactance

vs.

Height

Over Perfect Earth

These figures, too, appear to be highly accurate, and vertically-polarized mutual reactance is not very significant at HF when $H_\lambda > 0.70$ wavelength.

VI. SUMMARY.

While this report is not complex, it required so much computer and data reduction time that it discouraged any desire to include solutions for other antenna lengths. An analysis of computer solutions indicated the validity range of simplified equations was so narrow that such an approach is impractical. This is very apparent at heights, H_λ, greater than 0.15 wavelengths where solutions became oscillatory. Hence, all of the reduced data is plotted on the enclosed figures for general use.

The accuracy of these results depends upon the accuracy of the equations used in program subroutines. That is, with the exception of horizontal polarization and $0.01 \leq H_\lambda \leq 0.03$ wavelength over sea water, the curves on the figures are continuous, and the results are highly predictable. The highly accurate results on Figures 42-51 indicate that computational errors will be more related to the Hertzian parallel electric π_x component equation than to the Hertzian perpendicular electric π_z component equation used in the program Sommerfeld subroutine.

As noted above, solutions plotted on Figures 12-21 and 32-41 are oscillatory when $H_\lambda > 0.15$ wavelength. The individual figures suggest that R_{21} and X_{21} solutions are highly sensitive to frequency when the earth's permittivity is highly conductive. When the figures are reviewed collectively, frequency is less important than the earth's permittivity. This leads to the conclusion that the frequency, per se, effect is more one of length, L, effect where length at first resonance is a function of the length-to-diameter, L/D, ratio equation 4 in Reference 4.

The practical L/D ratios used in this report are plotted on Figure 52, where No. 12 wire (D = 0.08081 inches) was used at 2-26 MHz and 1.0 inch diameter tubing was used at 30 MHz. Thus, the 6 MHz first-resonant dipole is 0.3% shorter than the 2 MHz first-resonant dipole, the 10 MHz first-resonant dipole is 0.5% shorter than the 2 MHz first-resonant dipole, the 14 MHz first-resonant dipole is 0.6% shorter than the 2 MHz first-resonant dipole, the 18 MHz first-resonant dipole is 0.7% shorter than the 2 MHz first-resonant dipole, the 22 MHz first-resonant dipole is 0.8% shorter than the 2 MHz first-resonant dipole, the 26 MHz first-resonant dipole is 0.9% shorter than the 2 MHz first-resonant dipole, and the 30 MHz first-resonant dipole is 3.1% shorter than the 2 MHz first-resonant dipole. This behavior is apparent near the max-min regions on Figures 12-21 and 32-41. It also gives an explanation for the relatively large capacitive solutions at 30 MHz on Figures 2-5 when the first-resonant dipole is very near the ground.

If the 30 MHz first-resonant dipole had been made of No. 12 wire, it would have been 2.1% longer than that of the 2 MHz first-resonant dipole, the NEC solution on Figure 4 would have been -82.9 ohms when H_λ = 0.002 wavelength, and the NEC solution on Figure 24 would have been -210.6 ohms when H_λ = 0.002 wavelength (approximate the 26 MHz solutions!) On the other hand, if the 30 MHz first resonant dipole L/D ratio had been the same as that of the 2 MHz first resonant dipole, the NEC solution on Figure 4 would have been -69.9 ohms when H_λ = 0.002 wavelength, and the NEC solution on Figure 24 would have been -202.8 ohms when H_λ = 0.002 wavelength (approximate the 14 MHz solutions!) Therefore, at low antenna heights, solutions are highly dependent upon dipole length.

The behavior of mutual R_{21} and X_{21} vs. H_λ for the 5 defined near earths can be presented in general terms when frequency [and L/D] dependence is eliminated. The horizontally-polarized results at all 8 frequencies were averaged for each earth, and the average results vs. H_λ are plotted on Figures 53 and 54. These results show:

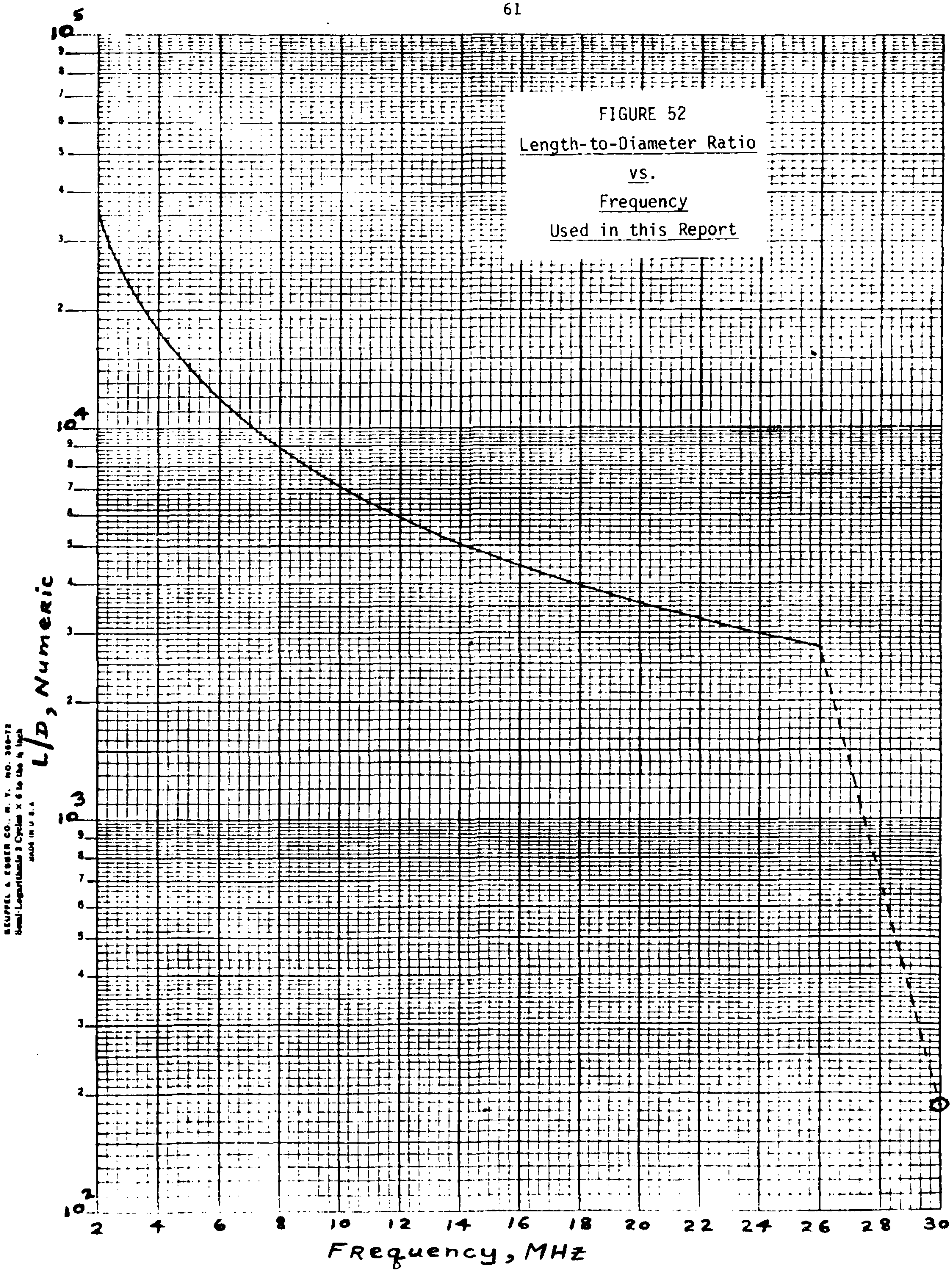

FIGURE 52
Length-to-Diameter Ratio
vs.
Frequency
Used in this Report

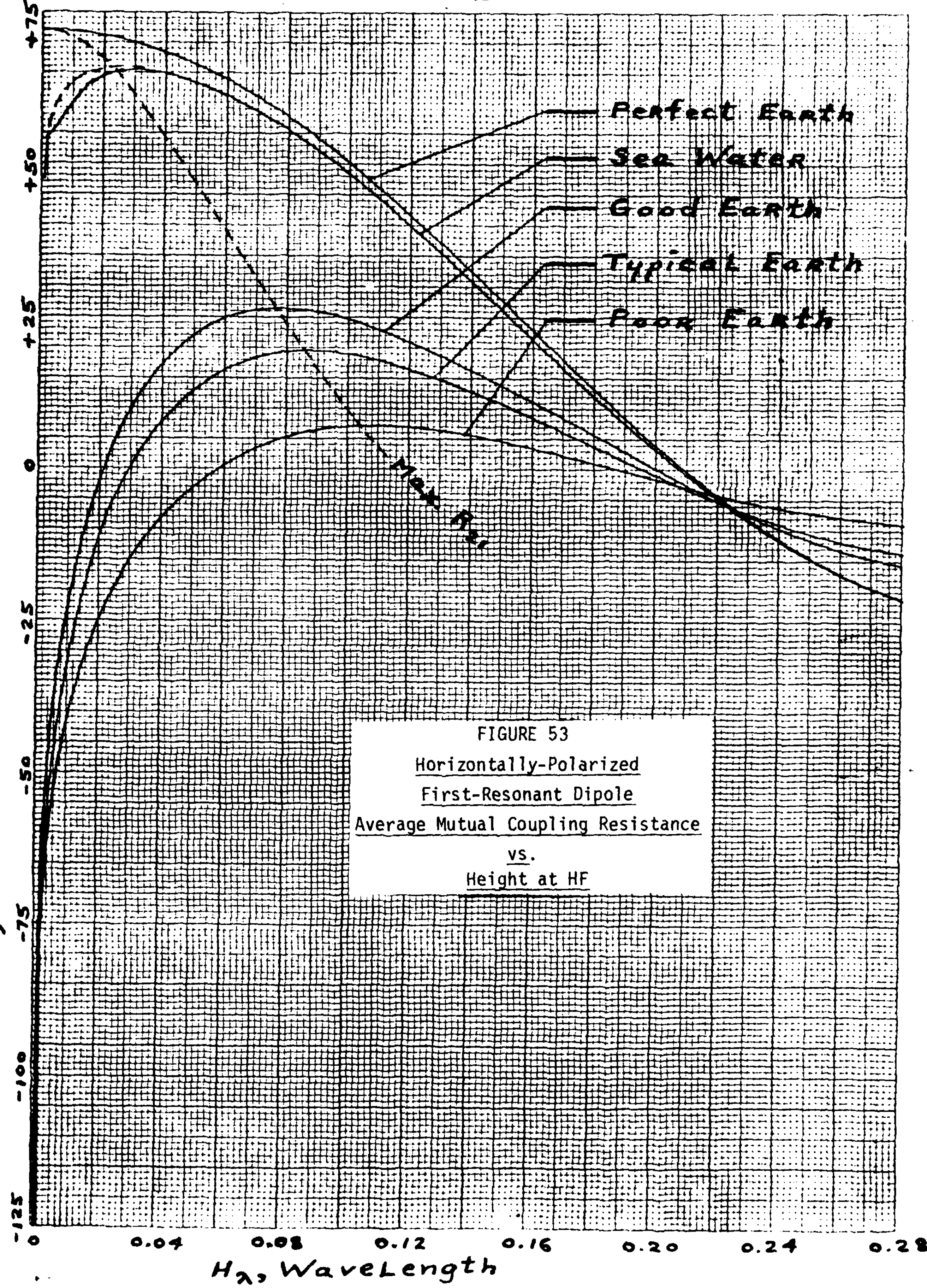

FIGURE 53

Horizontally-Polarized

First-Resonant Dipole

Average Mutual Coupling Resistance

vs.

Height at HF

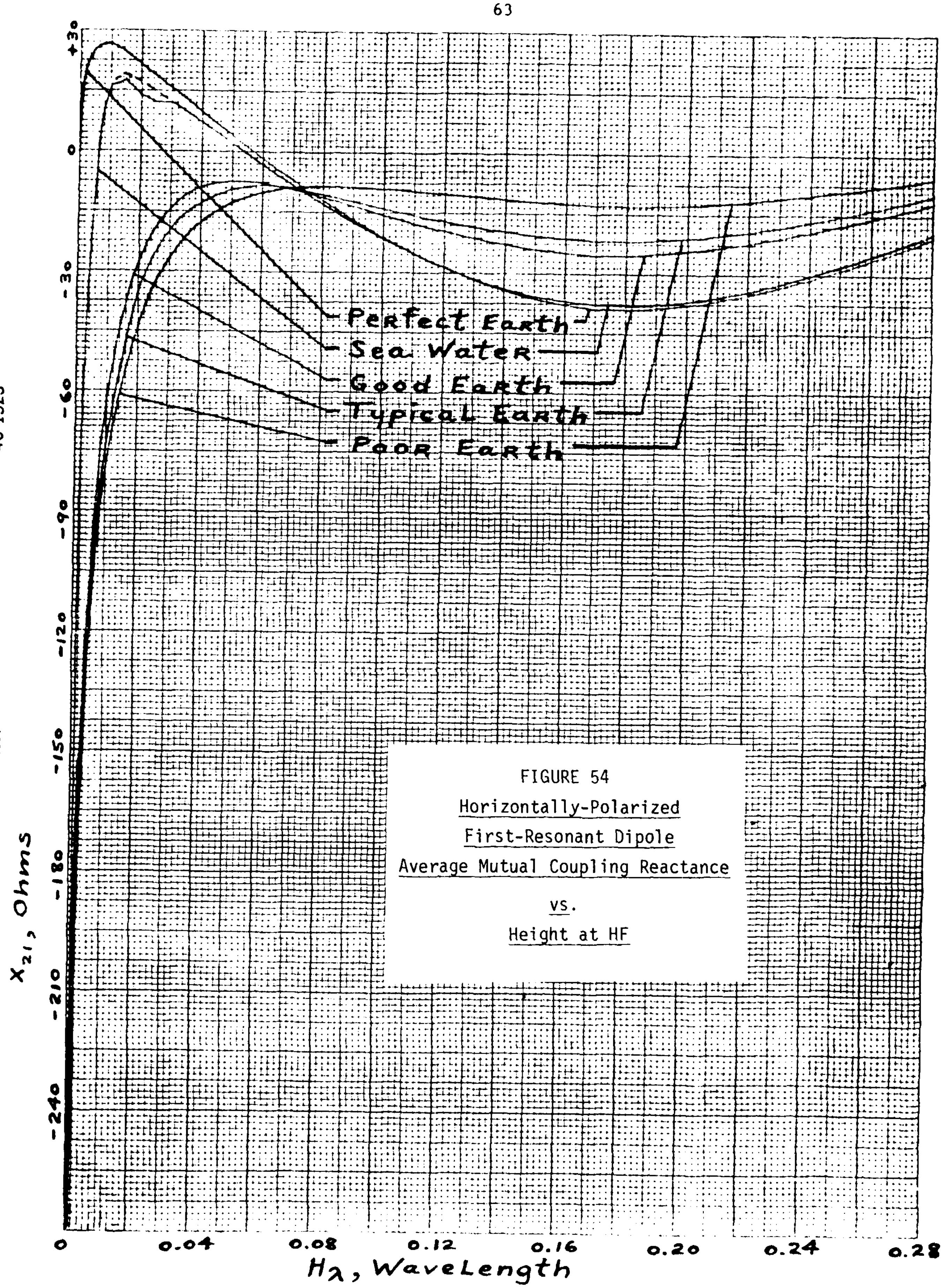

FIGURE 54

Horizontally-Polarized

First-Resonant Dipole

Average Mutual Coupling Reactance

vs.

Height at HF

1. The inaccuracy of NEC in the $0.01 \leq H_\lambda \leq 0.03$ region over sea water.

2. Both R_{21} and X_{21} have maximum values as a function of earth's electrical properties.

3. The height, H_λ, at which maximum R_{21} and X_{21}, occur depends inversely upon how good the earth is as a conductor.

4. With the exception of sea water and perfect earth, the mutual impedance terms, R_{21} and X_{21}, are highly negative when the horizontal first-resonant dipole is very near the earth.

While the results presented in this report are not precise, they are as accurate as one can expect without resorting to solutions involving a large number of L/D ratios. The problem is, as it turns out, that solutions are as much a function of first-resonant dipole length as they are to the electrical properties of the earth beneath the dipoles.

I am indebted to a number of PED personnel. Mr. Danny Fink set up the programs. Ms. Lee Ann Sampson and SP5 Virgil Brown were the terminal operators. SSG Robert Pulliam, SP5 Alvin Mack, and Mr. Steve Aubrey collated the stacks of printouts. Without the coordinated effort, of all, this lengthy report would have been impossible.

* *

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7. R. Corry, S. Holmes, and G. Lane, "Low Profile Dipole Antenna Design for Near-Vertical Incidence Sky-Wave Communication," EMEO-PED-80-5, p. 7; June 1980.

8. R. Corry, "Partial Validation of the Numerical Electromagnetic Code Computer Program Using Data Measured in Thailand," EMEO-PED-80-8, p. 9; September 1980.

9. In a 1968 discussion with U.S. Army Signal Corps Officer LTC L.F. Kruse, retired (now deceased), he had noticed a number of years earlier that first-resonant horizontal dipoles at Ft. Huachuca had to be shortened when set up at the same height over better earth in Missouri.